OPTIMIZING HULL STRUCTURAL DESIGN WITH ALUMINUM AND HYPOTHETICAL MATERIALS

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by

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ABSTRACT

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This thesis performs a modification of a computer program for the design of a midship section. The modification allows materials other than steels to be used. The previous version of the program had been extensively tested and proven, using both medium steel and high strength steels. To exercise and test the modified version of the program, various hypothetical combinations of modulus of elasticity and yield strength were used as input "materials." Test runs were also made with the properties of aluminum. Tests were conducted with steels to confirm that the previous results could be duplicated after the modifications had been made.

The program was formulated under merchant ship classing criteria of the American Bureau of Shipping. The modified version reflects changes, current to 1969, made to the A.B.S. Rules since the last version of the program was written. The logic and limits of the program should allow substitution of Naval standards or other systems of classing. This author does not agree that this can be "easily done", as was previously stated.

The program is large; it will not fit the WATFOR compiler. The source listing for the program is retained by the Department of Naval Architecture and Marine Engineering at M.I.T.

Documentation of the program, detailed instructions for preparation of input data, sample data and sample computer output are included as appendices to this thesis.

Thesis Supervisor: J. Harvey Evans
Title: Professor of Naval Architecture

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Throughout this work the author has continually relied upon previous work in the field of computer-aided ship design and structural analysis. Related work at M.I.T., including this thesis, has been initiated and guided by Professor J. Harvey Evans. His penetrating questions and assistance in formulating this work are gratefully acknowledged. This work is a direct extension of the previous five versions of the midship section design program, and the labors of all those who created them is acknowledged.

Acknowledgement is also due to my wife, Louise, for typing the thesis and for maintaining sanity in the household during "thesis time."

A special word of acknowledgement is also extended to Rodney Watterson for allowing my encroachment onto his desk, when my own was covered with computer printout and Fortran cards.

All computer calculations were performed at the M.I.T. Information Processing Center. Invaluable troubleshooting assistance was rendered by Dick Steinberg, of I.P.C.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

NOMENCLATURE

All symbols are defined locally. For the convenience of the reader, this nomenclature is collected below in alphabetical order. Greek symbols used are listed separately, in the order of the first letter of their Engish spelling. All symbols may have slight local variations of meaning or local units.

a	Span of plating, usually in direction of applied loading (in)
b	Span of plating, usually perpendicular to direction of applied loading (in)
c	A constant or a boundary condition coefficient
c_a	Aluminum costs
c_s	Steel costs
C	A constant
C_{mo}	Modified "old" cost ratio
C_n	"New" cost ratio
C_o	"Old" cost ratio
E	Modulus of elasticity (psi)
E'	Prime symbols have been used throughout to signify new materials, other than steel.
f_a	Fabrication ratio; 10% greater than steel rate
f_s	Fabrication ratio; rate for steel
F_i	Factor which represents ratio of $\bar{\sigma}_i$ (allowable stress) to σ_y
F_T	Flange thickness of I beam (in)

F_W Flange width of I beam (in)

G_1 Factor which represents ratio of $\bar{\sigma}_1$ (allowable stress) to σ_{ult}

h Water head (ft)

I Moment of inertia, (usually $in^2 ft^2$)

k' A boundary condition coefficient

K Edge support condition; K = 1 for simple supports, K = 4 for clamped supports

KEY Print control symbol; KEY = 0 Print all, KEY = 1 Print summary only

M Bending moment (ft-lbs or in-lbs)

M.I.T. Massachusetts Institute of Technology

N A.B.S. plate factor, N = cbh/12

psi Pounds per square inch

s Span (ft)

t Thickness, usually of plates (in)

t_D Thickness of Mariner deck plating (in)

t_S Thickness of Mariner bottom shell plating (in)

w A distributed load (lbs/ft or tons/ft)

W_n "New" material weight ratio

W_o "Old" material weight ratio

W_D Web depth of I beam (in)

W_T Web thickness of I beam (in)

Z Section modulus ($in^2 ft$ or in^3)

Greek symbols used:

α	Used as a proportionality symbol
δ	Deflection (usually inches)
γ_a	Weight of light materials in "semi-aluminum" series
γ_n	Weight of "new" material
γ_o	Weight of "old" material
γ_s	Weight of heavy materials in "semi-aluminum" series
λ	Poisson ratio
π	Standard meaning; $\pi = 3.14159$
σ	A stress (psi)
σ_1	Primary stress, ship bending stress (psi)
σ_2	Secondary stress, plate-stiffener, girder bending stress (psi)
σ_3	Tertiary stress, plate bending stress (psi)
σ_{ABS}	Apparent allowable stress implied by A.B.S. Rules; = 20,200 (psi) for medium steels
$\sigma_{ABS}(x)$	Allowable stress, comparable to σ_{ABS} for steel, for any other material
σ_{cr}	Critical stress for buckling (psi)
$\bar{\sigma}_i$	Allowable stresses for design (i = 1, 2 or 3)(psi)
σ_{ult}	Ultimate strength (psi)
σ_y	Yield strength (psi)

CHAPTER 1

INTRODUCTION

Throughout man's history, whenever he has created a need to transport large loads, he has resorted to a water borne vehicle. Unable, himself, to carry much more than 50 - 100 pounds for a distance of about 20 miles per day; man has constantly searched for easier ways. Land transport vehicles have progressed from mule back and horses through carts and wagons to todays' modern trucks and trains. Cargo hauling capabilities have increased from less than a ton carried about 30 miles per day to 15 or 20 tons per truck or 20 - 40 tons per rail car over distances of about 400 miles per day. Coupling 20 or 30 mules into a train or several hundred modern rail cars into a train multiplies the total load carried, of course; but the totals still fall far short of those possible with water transportation. In 1550 B.C. stone oblisks weighing 700 tons were transported on the Nile. [1]* This tonnage far over-shadowed all contemporary land transport of the day; as the almost unbelievable tonnages of the modern super tankers and giant bulk carriers overshadow their contemporary competition.

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* Numbers in square brackets refer to References at end of paper.

Ship owner's demands have always pushed the naval architect toward greater load carrying capacity. One of the many decisions affecting the success of every ship design is - What percentage of the total ship weight must be devoted to self-supporting and load-supporting structure?

The ever present demand to reduce the percentage of total weight devoted to structural members has recently led to increased use of both high strength and low weight materials in ship design and construction. High initial cost of the special purpose steels and of the light weight metals, such as aluminum, have, however, impeded their wide spread use.

The earliest and most extensive uses of these materials have occurred in "special use" vessels; where the cost considerations have been over-ridden by the uniquiness of the tasks that the vessel is designed to fulfill. Military ships fall in this category and the United States Navy has been among the leaders in utilizing light weight and/or high strength materials, especially for superstructures. The phenominal growth of complex electronic equipment, with the associated antennas which must be located high in the ship, has been one of the main factors driving designers toward lighter superstructure and topside weights.

In merchant vessels, the initial use of light weight materials, aluminum being the one of most widespread use, was limited to outfit and furnishings. Eventually ladders, exteriors of stacks, masts, and entire superstructures were

constructed of aluminum. The list below indicates estimates of weight savings possible in various areas. The saving is expressed as a percentage of the equivalent steel weight. [2]

Superstructure	35% of steel weight
Davits and life boats	47%
Outer stack	48%
Gratings	49%
Heating coils	43%
Piping, ladders, hatch covers, windows	31 - 36%

With increasing developments in metallurgy, the use of high strength materials in hulls, as well as superstructures, has been actively explored and utilized. In the case of high strength steels, and most other metals, the specific weight of the alloy is almost unchanged from that of the base metal, when strengthening by alloying. The weight savings are realizable due to reductions in the sizes and thicknesses of shapes and plates needed to support the specified loadings. Unfortunately most applications, to date, have been hampered by the various existing classification societies' rules. These rules, in general, apply to conventional construction of conventional hull forms with conventional metals, and they do not permit full realization of the new materials' potentials.

Any attempt to date the interest in such lightening of structrual weight would be pointless. One well documented paper presented in 1942 to the Society of Naval Architects

and Marine Engineers dates the level of professional interest at that time. [3] Since that time many papers have been published on the subject. (References [2, 3, 4, 5 and 6] represent only a very small percentage, but were of particular interest to the author)

In the field of entire hulls of light weight metals, specifically aluminum, a few specific dates are worthy of mention. In 1894 Yarrow and Company, an English firm, built "La Foudre," a 60-foot aluminum torpedo boat, for the French Government. Despite the high cost, this vessel was built entirely of aluminum. Thicknesses were fifty percent in excess of those used in similar boats of steel construction. Two and one half tons of weight were saved; in a vessel that weighed only ten tons when complete, with machinery. This was a savings of 25% and contributed greatly to the vessels' attainment of 20.5 knots average speed during full-power trials. This represented about a three and one-half knot speed advantage over contemporary craft of the same type. The hull was not able to withstand the marine environment, however, since an aluminum-copper alloy had been used. [7] This poor corrosion resistance and the high cost were to prevent aluminum from achieving wide acceptance in the marine field for many years.

The United States Navy experimented with limited use of aluminum in two torpedo boats in 1899. Great use was not made of this light metal until 1926, however. Under the Washington Disarmament Treaty Limitations the displacements

of capital ships was restricted. Hence the weight savings possible with aluminum assummed new importance. New construction and major conversions from that time to the present have made extensive use of aluminum, except during the war years when aluminum usage was restricted. Usage of aluminum for hulls of any appreciable size did not appear until roughly the 1950's. During 1948 - 1950 four aluminum hulled PT boats were built for the U.S. Navy. These ranged from 89 to 105 feet in length, and some were of riveted, welded and mixed riveted-welded hull construction. The Navy is presently receiving from contractors all aluminum motor boats (PGM class) of 164 feet in length. Many smaller vehicles such as landing craft and other amhibious craft are also being built of aluminum.

Special purpose craft being built for the Navy, including ground effect machines and skimmers and experimental hydrofoil craft, make extensive use of aluminum. The largest hydrocraft in use by the Navy is 220 feet in length, 40 feet in beam and displaces 300 tons. Over 110 tons of aluminum were used in construction of this vessel.

Modern destroyer-type ships are being designed with extensive topside aluminum components that result in about 150 tons of weight savings over comparable steel designs. Many designers and naval architects are advocating an all-aluminum destroyer, predicting a stronger, lighter and faster vessel. The prediction is based on taking half of the expected weight

savings and putting it back into the ship as a stronger hull, still lighter than the steel hull and thus capable of greater speeds with the same power plant.[8]

In the merchant marine the same trend toward larger and larger all-aluminum hulls is evident. The largest now in service is believed to be the "Sacal-Borincano." The ship was placed in service in June of 1967. It is called - "the largest all-aluminum ship ever built" and - "the first large ocean-going commercial vessel with an aluminum hull." Benefits claimed over a steel design include - "reduced draft by two feet, increased speed by one knot, savings in fuel, improved stability, and maintenance dramatically reduced."[9]

Thus ALUMINUM seems to have come of age as a ship building material; and a need exists for a midship section design program that will handle materials other than steels.

CHAPTER II

HISTORY OF THE MIDSHIP SECTION DESIGN PROGRAM

The history of any computer program starts with the pre-establishment of a manual system for accomplishing a particular task. There have been many ways of deciding the scantlings of the midship section - the earliest was presumably a good guess which proved capable of sailing the seas and returning. It should be emphasized that the "returning" was of primary concern and this requirement rapidly developed into "return with a profitable cargo." Hence, we define again the designer's controversy: the hull structure must have enough strength (which is also to say weight) to support the ship, with cargo, etc., at sea, in all weather, and yet must allow as much reserved weight and space as possible for cargo.

Over the years of trial and error, a considerable history, both of successes and failures, has accumulated. From this accumulation certain thumb rules can be extracted as being vitally necessary to a successful design. Review, evaluation and codification of such data is the work of the various classification societies. "Rules for Building and Classing Steel Vessels" by the American Bureau of Shipping (called A.B.S. Rules) is one example of such a codification. [10] This comprehensive body of data has for many years

formed the lower limit measure of structural adequacy based on actual operational experience.

Unfortunately, as occurs in almost all instances when rules are published, there are a certain number of cases that fall outside the range of tabulated experience; and outside the range to which the rules may sensibly be extrapolated. As newer materials and construction techniques are tested and found suitable for structural use, the need for wider and more comprehensive design techniques is evident. This is not to say that the wealth of "past experience" should be discarded or ignored; but rather it should be tempered with the knowledge of newer materials and their capabilities and extended on the basis of elementary and analytic concepts.

The history of the attempt, at Massachusetts Institute of Technology (M.I.T.), to establish a design procedure based on such concepts is concerned mainly with the work of Professor J. Harvey Evans, of the Department of Naval Architecture and Marine Engineering.

In 1958 Evans presented a paper to the Society of Naval Architects and Marine Engineers (SNAME) entitled - "A Structural Analysis and Design Integration...with Application to the Midship-Section Characteristics of Transversely Framed Ships." [11] This paper was an attempt to establish a rational design method for the longitudinally effective structural material of a ship's hull. M.L. Sellers,

in his discussion of Reference [11], summarized the feelings of many Naval Architects and others in the marine design and construction field. The first, often quoted, paragraph and the last paragraph of Sellers' discussion are quoted below:

> "When introducing young designers to the art of ship structural design, in order to make them have the proper respect for their work, we usually go to great lengths to impress upon them the magnitude of their task by pointing out that a ship is an elastic structure weighing thousands of tons which is driven at a speed of many miles per hour through ocean waves. As such, the structure is subject to large static and dynamic forces and operates in a corrosive medium and has to last for many years which means, in short, that a modern ship is an engineering marvel. After this build-up, we know there is a tremendous let-down in the minds of these fellows when we produce the rules of the classification societies and show them that scantlings for these engineering marvels can be determined about as easily as reading a time table. That such a situation does exist is of course a tribute to the great work done by these societies."
>
> "In this paper the author has given us another tool to assist in bridging the gaps between theory, experiment, and practice. While there appear to be some inconsistencies in the rules, the paper does demonstrate that scantlings which are satisfactory for service can be expressed in the terms of simple formulas. Once this is done we have a basis for further analysis and extrapotation."

Certainly not all discussions of the paper, in fact not all of Sellers' discussion, were as complimentary to the author. Each discussion did, however, in one form or another, express much of the sentiment of Sellers' last paragraph.

"Once this is done we have a basis for further analysis and extrapolation." This was the vital step necessary for computerization also. Once the intricacies of the A.B.S.

Rules were reduced to formulas of proven match to the rules, the stage was set for eventual computerization of the lengthy, trial and error, iterative process of finding "the best design."

Briefly the process suggested is one of determining, through instability criteria and stress formulas, the minimum thickness of hull plating and other effective load carrying longitudinal structure. Once an initial sizing of each effective member is determined, a section modulus may be computed and checked for adequacy. Modifications may then be made to appropriate scantlings to attain a satifactory section modulus from the viewpoint of hull girder bending. Many, many cycles or iterations are necessary to find the optimum solution. These iterations are the exact endeavor for which a computer solution is ideal.

From Evan's 1958 paper have sprung many studies in the field of systematic analysis of ships' structures. At M.I.T., under Evans' direction, such studies have resulted in a detailed design computer program that has been well tested and proven. Many persons have contributed to this effort and only a few of them are represented in a listing of the major steps of the programs' evolution. To these unsung contributors is due a fitting measure of credit. The major milestones of the program itself are these:

1) Weight-Strength Analysis of Cargo Ships' Structures by Dan Khoushy, 1962. [12]

2) Optimized Design of Midship Section Structure by J. Harvey Evans and Dan Khoushy, 1963. [13]

3) Computer Applications to the Design of a Combination Framed Midship Section, by Charles Roth and Donald Liu, 1966. [14]

4) Optimization of Primary Hull Structure with Mixed Framing Systems, by Robert D. Rockwell and Otto P.J. Jons, 1967. [15]

5) Optimizing Hull Structural Design with High Strength Steels, by J. Harvey Evans, 1967. [16]

Each of the above have modified and updated and/or tested the then current version of the computer program. Initially designed to handle only transverse framing systems, the program will now handle transverse, longitudinal and mixed framing systems. It has been used in exhaustive parametric studies to define optimum least weight and least cost designs and has been used to determine the optimum distribution of various combinations of high strength steels. [12, 13, 14, 15 and 16] Not until this work, however, have materials other than steels and materials with varying elastic modulus been investigated with the program.

CHAPTER III

MODIFICATIONS TO THE COMPUTER PROGRAM

General Comments on Modifications

As stated in Chapter II many authors' variations have contributed to the present version of the program. Many statements in previous theses, concerned with the midship section program, have indicated that the program was written in very general terms. As initially envisioned, any modifications to the program were to be a very minor part of this thesis. The main effort was to be directed toward an economic study of the cost effectiveness of utilizing aluminum as a hull material, knowing that a significant premium must be paid for material cost. The question to be answered was - Could the optimum midship section design save enough hull structural weight to pay off the material cost premium in a reasonable length of time and then earn the owner a larger profit?

It was found that the program was functionally designed to be general but that realistically, as written, it could handle only steels. Many instances were found where variables such as specific weight were written in as constants, (0.283 pounds per cubic inch for steels) rather than as a variable from the array of material properties. There is no record whether this was an expedient to meet some past thesis deadline or merely fore-knowledge that only steels would be used in the immediate future.

The section that designs the transverse structure, which was a separately designed addition to the program, was based entirely on medium steel formulas, with pre-computed constants determined by fitting the formula to the American Bureau of Shipping (A.B.S.) Rules. These formulas were constructed in a manner that made no allowance for variations in properties, modulus of elasticity or yield strength, from the values for medium steel.

Although the program was written to handle the design of the midship section using more than one metal and although the program has been successfully utilized in this fashion, the success achieved depended on the fact that all the combinations of materials used were steels. (Reference [16] used three sections Bottom, Side and Top, or main deck, with locations of the interfaces a variable) Combinations of other materials, or of steels with other materials would not have worked.

Early in the preparation of this thesis, it became apparent that the modification of the 75 subroutines of this program, amounting to almost 6000 Fortran cards, was a task of signicantly larger proportions than had been previously anticipated. As a result the portion of the time budget originally scheduled for the cost effectiveness analysis of the results of this study was re-directed toward the thorough modification of the program to enable any material

or combination of materials to be utilized. Another tangent was added at this time also. It was decided to run a parametric study of the effect of variation of combinations of modulus of elasticity and yield strength.

The "hypothetical materials" that were "constructed" have the following properties - modulus of elasticity varies from 10×10^6 (psi) through 40×10^6 (psi), in steps of 10×10^6 (psi); yield strength varies from 30×10^3 (psi) through 150×10^3 (psi), in steps of 40×10^3 (psi). These various hypothetical materials present a matrix of sixteen possible combinations; for each of which the "optimum" frame spacing is desired.

One of the major obstacles encountered in attempting to modify the old version of the program was the myriad of cryptic abbreviations used as Fortran names for the variables. In order to modify the program intelligently it was first necessary to dissect it, in the smallest detail, to learn not only what each variable name meant but also what each element of each variable array contained. This effort has caused the author to recommend that a tabulation of the sort found in Appendix 2 be a requirement for future computer programs; especially those that are liable to be expanded and modified. This subject is discussed in more detail in the section on recommendations for further study.

The remainder of this chapter is divided into two parts-Modifications to Data Deck Setup and Modifications to Accomodate Variable Material Properties.

Modifications to Data Deck Setup

The previous program (program version 5) is ideally setup for parametric studies. The data input system is extremely flexible allowing almost all variables to be varied at will. Any of the data input sections ($MS ******) can be changed individually. (With due regard to keeping the number of materials in the $MS PROPERTIES OF MATERIALS section equal to the number of cost sets in $MS COST section and having $MS COST data always follow the $MS PROPERTIES OF MATERIALS data in the data deck setup) Only two major changes were made in the data deck setup; and one of these was more on the order of an addition to the system, rather than a modification.

A separate data section "PROPERTIES OF MATERIALS" was created and a new subroutine, called PROMAT, was constructed to read in the properties of the various materials that the program would utilize. The old "MATERIAL" section was renamed "MATERIAL ASSIGNMENT" and presently handles only that explicit task; reading in the assignment of particular materials to the various sections of the ship.

The other major change concerns an indicator to control the printed computer output. Basically this indicator permits either all detailed intermediate results and the summary or only the summary of results to be printed.

A separate section, Appendix 3, explains, in step-by-step fashion, the construction of a sample data deck. Appendix 4 contains a copy of a sample data deck.

The reasons and mechanics of the above changes, and a few other minor changes, follow:

In the previous program the properties of the metals to be used during computation were inserted in the Fortran source deck of the program as DATA statements. They could be changed at will by simply exchanging new cards for old. The length of the program and the resultant cost for reading in and compiling the Fortran source decks for each data run, led to the conclusion that operation with a compiled binary, or object, deck would be much more efficient. This certainly proved to be the case.

To permit the changing of the materials while operating with the binary deck, a new subroutine (PROMAT) was constructed to read in the properties of each material desired and from these properties to compute the allowable stresses to be used later as design limits. The subroutine data input format for PROMAT is detailed in Appendix 3.

The subroutine PROMAT expects to read first the number of materials to be read in. This number is limited to five or below. This same number is used in the INCOST subroutine for reading in cost data for each material. Because of this the material data ($MS PROPERTIES OF MATERIALS) must always

precede the cost data ($MS COST DATA) in the data deck setup. The number of sets of cost data (cost of plates, cost of stiffeners, and labor factor) submitted must always match the number of materials submitted as data.

PROMAT next expects to read two cards for each material. The first card contains the material type number, for identification, the yield strength, the ultimate strength and an allowable stress factor. The second card contains the modulus of elasticity, Poisson ratio and the weight of the material. The allowable stress factor and Poisson ratio are dimensionless. The weight must be in units of pounds per cubic inch. All other properties are in units of pounds per square inch.

The allowable stress factor permits two methods of selecting the allowable primary, secondary and tertiary stresses. Allowable stresses are called $\bar{\sigma}_1$, $\bar{\sigma}_2$ and $\bar{\sigma}_3$, as defined in [11], with the usual meanings: σ_1 = ship bending stress, σ_2 = girder bending stress (plate-stiffener combination), and σ_3 = plate bending stress.

The previously published and generally accepted figures of σ_1 = 20,000 (psi), σ_2 = 27,000 (psi) and σ_3 = 32,000 (psi) for a medium steel, with a yield strength of 32,000 (psi) and an ultimate strength of 60,000 (psi), were used as a basic starting point. The numbers, listed as "Based on σ_y and σ_{ult}" in Table 3 of Reference [16], were obtained by

Evans in the following manner. A factor relating each sigma stress to the yield strength and another factor relating each to the ultimate strength were defined:

$$F_i = \frac{\bar{\sigma}_i}{\sigma_y} \qquad G_i = \frac{\bar{\sigma}_i}{\sigma_{ult}}$$

F_1 is therefore defined as:

$$F_1 = \frac{\bar{\sigma}_1}{\sigma_y} = \frac{20000}{32000} = 0.625$$

The values of F and G are:

$F_1 = 0.625$ $\qquad$ $G_1 = 0.3333$

$F_2 = 0.84375$ $\qquad$ $G_2 = 0.450$

$F_3 = 1.0$ $\qquad$ $G_3 = 0.5333$

Using these values, $\bar{\sigma}_i$ based on σ_y and $\bar{\sigma}_i$ based on σ_{ult} can be found:

$$\bar{\sigma}_i = F_i \sigma_y \qquad \bar{\sigma}_i = G_i \sigma_{ult}$$

Thus two limiting values of allowable stress are generated; one based on σ_y and one based on σ_{ult}. There is little agreement as to which should be used as the base for limiting design stresses.

R.G. Kline has dealt with high strength steels, under brittle fracture and fatigue conditions. [4] He concluded

that acceptable allowable stresses for high strength steels, with σ_y = 50,000 (psi) and 100,000 (psi), could be generated by simple multiplication of the accepted allowable stresses for medium steel by 1.3 and 1.8, respectively.

The allowable stresses generated by the above methods are shown in Table 1. This table is a reproduction of Table 3 of Reference [16]. To it have been added the various alternatives which may be generated by the present (version 6) program.

In general, the allowable stresses generated by Kline fall roughly mid-way between those based on σ_y and σ_{ult}. The values used for calculations in Reference [16] were Kline's values with some small changes made in the allowable tertiary, or plate stress, values. It was decided to construct the program in such a manner that the user could modify the medium steel allowable stresses by either a simple multiplication factor, such as Kline proposed, or have the program generate the average between the ratioed values based on σ_y and σ_{ult}.

The "Allowable Stress Factor" listed as an input in the $MS PROPERTIES OF MATERIALS data section is used to select which method will be used to set allowable stresses within the program. If the Allowable Stress Factor is set equal to 1.0 then each medium steel allowable stress is multiplied by 1.0 and the medium steel allowable stresses result. If any

Table 1

Allowable Stresses

(Table 3 of [16] with additions)

	MS			HTS			HY		
σ_y (psi)	32,000			50,000			100,000		
σ_{ult} (psi)	60,000			70,000			115/135,000 (115,000 used)		
	$\bar{\sigma}_1$	$\bar{\sigma}_2$	$\bar{\sigma}_3$	$\bar{\sigma}_1$	$\bar{\sigma}_2$	$\bar{\sigma}_3$	$\bar{\sigma}_1$	$\bar{\sigma}_2$	$\bar{\sigma}_3$
Presumed general practice	20,000	27,000	32,000						
Based on σ_y				31,300	42,200	50,000	62,500	84,400	100,000
Based on σ_{ult}				23,300	31,500	37,400	38,000	52,000	61,000
From Kline [4]				26,000	35,000	41,500	36,000	48,500	57,500
Values used [16]	20,000	27,000	32,000	26,000	35,000	45,000	36,000	48,500	60,000
Values generated by program									
F = 1.0 (Medium Steel)	20,000	27,000	32,000						
F = 0.0	20,000	27,000	32,000	27,290	36,845	43,665	50,415	68,065	80,664
F = 1.3 (Kline [4, 16])				26,000	35,100	41,600			
F = 1.8 (Kline [4, 16])							36,000	48,600	57,600

other positive (non-zero) Factor is set in as input, the same sort of multiplication of the medium steel allowable stresses by that Factor occurs, to generate new allowable stresses for the new material. If the Allowable Stress Factor is set equal to zero, the program utilizes the previously stated values of F_i and G_i and the σ_y and σ_{ult} values of the material to generate the average of $\bar{\sigma}_i$ based on σ_y and $\bar{\sigma}_i$ based on σ_{ult}. These averages then become the allowable primary, secondary or tertiary stresses (depending on the value of i) used in the program.

To control the printed output, all print subroutines, except the summary subroutine, are set-up to be keyed by an input indicator, called "KEY." When KEY is set equal to zero (KEY = 0) all subroutines will print. This gives the user all the detailed intermediate results as well as the summary of results. When KEY is set equal to one (KEY = 1) only the summary subroutines will print. This summarization always includes the print out of final plate thicknesses. Plate thicknesses were considered desirable results even if only the summary printout is requested.

When parametric studies are being conducted the results desired are provided by the summary. Total weight and cost per foot, and weight breakdown into transverse and longitudinal structure are printed. Longitudinal weights are further broken into weights of various materials when more than one

material is used. Cost is broken into material cost and labor cost subtotals.

Two ratios are provided also by the summary. These are a weight ratio and a cost ratio and are formed with input base weight and base cost. Most studies done at M.I.T. to date have used the Mariner hull; and the base weight and cost figures used represent this hull: transversely framed, made entirely from medium steel, and with a frame spacing of 2.5 feet.

Details provided by the remaining print subroutines include: coordinate locations of all plate seams and all stiffeners; head loadings at each of the above locations; bottom structure weights; area, moment, and inertia constants used; initial plate thicknesses assumed; initial stiffener sizes assumed; final stiffener sizes; final plate thicknesses; transverse weight breakdown; deck and shell frame weight breakdown; cost breakdown.

When designing a midship section, naturally the user will want all the design details printed out. For parametric studies of a large number of ships, or many variations of the same ship, however, the user will probably be satisfied with the summaries. This may be the case for the designer above also, until the optimum has been found; then a rerun "keyed" to print all detail would provide the "design." The difference between KEY = 1 and KEY = 0 is about twenty pages of printed output.

Another minor change provides for several materials to be displayed in the STRUCTURAL DATA input section. This section prints the bending moment to be designed for, the limiting design stress and the resulting required section modulus for both bottom and upper deck areas. Previously only one material could be entered here. This information is not used within the program and is printed out only for comparison with the program generated values of section modulus. If desired the program will generate this data using familiar formulas for medium steel, when no data is provided as imput.

Another change provides for the selection of the material used for design of the transverse structure. In the previous version all transverse structure was of medium steel. This made some sense when constructing of high strength steels for longitudinally effective material, as it would probably be the practical solution to design the transverse structure of the cheaper medium steel. This can still be designed in, if desired, since the material for transverse structure is a separate selection made in the $MS MATERIAL ASSIGNMENT section.

A data check was written into the subroutine INCOST, which reads in the cost data, to prevent accumulating a different number of sets of material properties and sets of cost data. This check requires these numbers to be matched and hopefully helps avoid costs being matched with wrong materials or no costs being entered for some material, etc.

Modifications to Accomodate Variable Material Properties

The computer program has been constructed to satisfy the following basic design equations:

$$\sigma_1 \leq \bar{\sigma}_1$$

$$\sigma_1 + \sigma_2 \leq \bar{\sigma}_2$$

$$\sigma_1 + \sigma_2 + \sigma_3 \leq \bar{\sigma}_3$$

Sigma bar quantities ($\bar{\sigma}$) represent allowable stresses. Un-barred quantities (σ) represent nominal hull stresses. [11,13 and 16]

These design equations are based on medium steel, where the ultimate strength is roughly a factor of two times the yield strength. Provisions were made in the modified program to allow the user to adjust the allowable stresses by ratios related both to the yield and the ultimate strengths of the material to be used. This modification was explained in the previous section since it was directly related to the data input of the new subroutine PROMAT.

Further modifications to the design equations were found to be necessary to permit the use of materials other than steels. These modifications were mainly associated with the section of the program that designs the transverse structure. In the longitudinal structure sections the design formulas are based on more elementary principles rather than directly on the A.B.S. Rules' formulas. The transverse structure design section is less rationally developed. It is

still directly related to the A.B.S. Rules and sizes transverse structural members using formulas derived from design loadings deduced from scantling tables of the A.B.S., and in a few cases taken directly from the Rules. [12]

Modifications to the Formulas For the Design of Deck Beams and Side Frames

Starting with the general bending moment equation:

$$M = \frac{ws^2}{k'} \times 12 \qquad (a)$$

and the relation: $\sigma = \dfrac{M}{Z}$ (b)

where: M = bending moment (in-lbs)

w = distributed load (lb/ft)

s = span (ft)

Z = section modulus (in^3)

σ = allowable bending stress (psi)

k' = boundary condition coefficient

The σ we are dealing with here is $\bar{\sigma}_2$, the allowable secondary or girder bending stress, for the beam. For purposes of identification of this particular stress, in the work following, it will be called σ_{ABS}, and specifically refers to medium steel unless otherwise noted.

From equations (a) and (b), Z is determined:

$$Z = \frac{12ws^2}{k'\sigma_{ABS}} \qquad (c)$$

The A.B.S. Rules define the required section modulus for beams as:

$$Z = 0.00315\ Ns^2 \qquad \text{(d)}$$

where: $N = cbh/12$ (e)

so that: $Z = 0.0002625\ cbhs^2$ (f)

where: c = a boundary condition coefficient

b = frame spacing (ft)

h = pressure head (ft)

Z = section modulus (in^3)

s = span (ft)

The computer program sizes the beam under consideration by forming a ratio of the required section modulus, from (f) above, to the section modulus of a standard stiffener. This ratio is called the proportionality factor and tells what proportion of the standard stiffener, either smaller or larger, is required.

If the section modulus, Z, is inversely proportional to the $\bar{\sigma}_2$ stress, as in (c); and if the material to be used has an allowable stress not equal to that of medium steel; then the required section modulus should reflect the differences in allowed stresses by requiring an inversely corresponding section modulus. An allowable stress that is smaller than $\bar{\sigma}_2$ would require a larger section modulus, etc.

Let $\sigma_{ABS}(x)$ represent the allowable stress of the new material (x).

Then: $$Z = \frac{12ws^2}{k' \ \sigma_{ABS} \times \dfrac{\sigma_{ABS}(x)}{\sigma_{ABS}}} \qquad (g')$$

$$Z = \frac{12ws^2}{k' \ \sigma_{ABS}} \times \frac{\sigma_{ABS}}{\sigma_{ABS}(x)} \qquad (g)$$

Hence the required Z for medium steel should be multiplied by the ratio of medium steel allowable stress to the allowable stress of the new material.

Another factor complicates this simple solution, however. The σ_{ABS} defined above is not the $\bar{\sigma}_2$ defined in the PROPERTIES OF MATERIALS section. Evans and Khoushy [13] found that by working backwards (with the knowledge of normal sizes for spans, construction practices, the usual range of stiffness and the extremes of 1.0 and 0.0 for the distribution factors for simple supports and fixed ends, respectively) the allowable stress implied by the A.B.S. Rules is 9 (tons/in^2) or 20,200 (psi).

As explained previously in the PROPERTIES OF MATERIALS section, this program uses the more generally accepted 27,000 (psi) for $\bar{\sigma}_2$, the allowable stress for medium steel. As found by Evans and Khoushy:

$$\sigma_{ABS} \text{ (steel)} = 20{,}200 \text{ (psi)} \qquad (h)$$

with: $$\bar{\sigma}_2 \text{ (steel)} = 27{,}000 \text{ (psi) as before} \qquad (i)$$

then: $$\sigma_{ABS}\ (\text{steel}) = 20{,}200 \times \frac{\bar{\sigma}_2(\text{steel})}{27{,}000} \qquad (j')$$

$$\sigma_{ABS}\ (\text{steel}) = 20{,}200 \times \frac{\bar{\sigma}_2(\text{steel})}{\bar{\sigma}_2(\text{steel})} \qquad (j)$$

where $\bar{\sigma}_2$ has its previously defined meaning:

$\bar{\sigma}_2$ = allowable secondary stress as computed in the PROPERTIES OF MATERIALS section

Therefore,

$\sigma_{ABS}(x)$ for any other material:

$$\sigma_{ABS}(x) = 20{,}200 \times \frac{\bar{\sigma}_2(x)}{\bar{\sigma}_2(\text{steel})} \qquad (k)$$

Now from (g), the required ratio for modifying the section modulus is:

$$\frac{\sigma_{ABS}(\text{steel})}{\sigma_{ABS}(x)}$$

This ratio is called Transverse MAterial RATio, or TMARAT, in the program.

$$\text{TMARAT} = \frac{\sigma_{ABS}(\text{steel})}{\sigma_{ABS}(x)} \qquad (l)$$

But, from (k):

$$\sigma_{ABS}(x) = 20{,}200 \times \frac{\bar{\sigma}_2(x)}{\bar{\sigma}_2(\text{steel})} \qquad (k)$$

and from (h) $\quad \sigma_{ABS}(\text{steel}) = 20{,}200 \qquad (h)$

Therefore: $$\text{TMARAT} = \frac{20{,}200}{20{,}200 \times \dfrac{\bar{\sigma}_2(x)}{\bar{\sigma}_2(\text{steel})}} \qquad \text{(m)}$$

$$\text{TMARAT} = \frac{\bar{\sigma}_2(\text{steel})}{\bar{\sigma}_2(x)} \qquad \text{(m)}$$

Hence, each time a beam section modulus is computed by the program it is modified by the ratio TMARAT.

Thus (f) multiplied by TMARAT becomes:

$$Z = 0.0002625\ cbhs^2 \times \frac{\bar{\sigma}_2(\text{steel})}{\bar{\sigma}_2(x)} \qquad \text{(n)}$$

Vertical side frame members are designed by the program in a like manner, using different formulas of course, resulting in a specific required section modulus. This required modulus is also multiplied by the ratio TMARAT to reflect material property variation.

Modifications to the Formulas For Deep Web Frame Design

A.B.S. requirements for deep web frame design are listed below:

Deck Frames	Side Frames
$W_D \geq .7 \times s$	$\geq 1.5 \times s$
$W_T \geq .01 \times W_D + 0.16$	$\geq .01 \times W_D + 0.14$
$W_T \geq .3 + .01 \times F_T \times F_W$	$\geq .56$

where: W_D = web depth depth (in)

W_T = web thickness (in)

F_W = flange width (in)

F_T = flange thickness (in)

s = span of member (ft)

0.16 and 0.14 additions are wastage allowances and were not modified

The Rules state the requirements for web frame dimensions in terms of minimums, with no reasons given. This leads one to speculate that this minimum limit is a stiffness criterion and presumably is based on a deflection limitation.

One such deflection criterion is:

$$\delta \leq \frac{s}{360}$$

or: $$\delta = f(EI)$$

$$\delta = \frac{ws^4}{cEI}$$ (for a distributed load w, span s, and simple support conditions)

where: δ = deflection (usually inches)

s = span (ft)

E = modulus of elasticity (psi)

I = moment of inertia (in^2ft^2)

w = distributed load (lbs/ft)

c = constant

To require the same limitation or same maximum deflection, when using a material other than steel, requires that:

$$\frac{ws^4}{cEI} = \frac{w'(s')^4}{c'E'I'}$$

where: prime quantities represent new material properties.

The end conditions, loading and span all remain constant.

Therefore: $$\frac{1}{EI} = \frac{1}{E'I'}$$

or $$I' = I \times \frac{E}{E'}$$

The program uses an I-beam to simulate the web frame member. The moment of inertia of an I-beam is found:

$$I \text{ about own axis} = I_{web} + 2I_{flange}$$

$$I_{web} = \frac{1}{12} W_T W_D^3$$

$$I_{flange} = F_T \times F_W \times \frac{W_D^2}{4}$$

Assuming $\frac{W_D}{2} \gg \frac{F_T}{2}$

Therefore: $$I = \frac{W_T W_D^3}{12} + 2x \frac{F_T F_W W_D^2}{4}$$

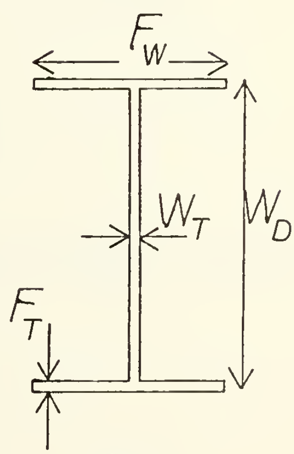

Fig. 1

I-Beam Detail

or $$I = \frac{W_T W_D^3}{12} + \frac{F_T F_W W_D^2}{2}$$

W_T and F_T are approximately equal

W_D and F_W are of the same magnitude

Therefore: I is proportional to W_D^3

$$I \alpha W_D^3 \qquad I' \alpha (W_D')^3$$

Since: $$I' = I \times \frac{E}{E'}$$

Then: $$(W_D')^3 \alpha (W_D)^3 \times \frac{E}{E'}$$

or $$W_D' \alpha W_D \times \sqrt[3]{\frac{E}{E'}}$$

The current program modifies W_D of the A.B.S. Rules by multiplying by the cube root of the ratio of the steel elastic modulus to the new material elastic modulus.

Thus: $$W_D \geq .7 \times s \times \sqrt[3]{\frac{E}{E'}}$$

In the program the ratio $\frac{E'}{E}$ is called EPRIE, and the above limit on W_D becomes:

$$W_D \geq .7 \times s \times \frac{1}{\sqrt[3]{EPRIE}}$$

Modifications to the Formulas For Span to Thickness Ratios

The program requires that the following proportions be maintained in web frame design:

$$\frac{W_D}{W_T} \leq 60. \qquad \frac{F_W}{F_T} \leq 10.$$

A similar requirement is imposed on vertical floors in the bottom design:

$$\frac{b}{t} \leq 96$$

where: b = span dimension of plate (in)

t = thickness (in)

These requirements are obviously to satisfy a buckling criterion.

For buckling: $$\sigma_{cr} = \frac{K\pi^2 E t^2}{12(1-\lambda^2)b^2}$$

where: σ_{cr} = critical stress for buckling (psi)

K = constant depending on aspect ratio

E = modulus of elasticity (psi)

t = thickness of plate (in)

b = span dimension of plate (in)

λ = Poisson ratio

Solving for $\frac{b}{t}$:

$$\frac{b^2}{t^2} = \frac{K\pi^2 E}{12(1-\lambda^2)\sigma_{cr}} = \frac{CE}{(1-\lambda^2)\ \sigma_{cr}}$$

$$\frac{b}{t} = \left[\frac{CE}{(1-\lambda^2)\ \sigma_{cr}}\right]^{\frac{1}{2}}$$

The relationship when the material is changed, where the prime quantities represent the new material:

$$\frac{\frac{b'}{t'}}{\frac{b}{t}} = \left[\frac{C'\ \frac{E'}{(1-\lambda^2)'\sigma_{cr}'}}{C\ \frac{E}{(1-\lambda^2)\sigma_{cr}}}\right]^{\frac{1}{2}}$$

and if $\sigma_{cr} = \bar{\sigma}_2$

$$\frac{b'}{t'} = \frac{b}{t}\left[\frac{E'}{E} \times \frac{\bar{\sigma}_2}{\bar{\sigma}_2'} \times \frac{(1-\lambda^2)}{(1-\lambda^2)'}\right]^{\frac{1}{2}}$$

As defined before: $\frac{E'}{E} = \text{EPRIE}$

$$\frac{\bar{\sigma}_2}{\bar{\sigma}_2'} = \text{TMARAT}$$

Define: $$\frac{(1-\lambda^2)}{(1-\lambda^2)'} = \text{PPPRI}$$

Now: $$\frac{b'}{t'} = \frac{b}{t}\,(\text{EPRIE} \times \text{TMARAT} \times \text{PPPRI})^{\frac{1}{2}}$$

Also define: $$\text{ESIGRA} = (\text{EPRIE} \times \text{TMARAT} \times \text{PPPRI})^{\frac{1}{2}}$$

Then: $$\frac{b'}{t'} = \frac{b}{t} \times \text{ESIGRA}$$

Thus any such buckling ratio limit that is imposed by the program is modified by the multiple ESIGRA.

CHAPTER IV

ALUMINUM INVESTIGATIONS

General Comments

The original scope of the aluminum investigation was drastically reduced when the magnitude of the computer program modification became evident. As completed, two different uses were made of the computer program during the aluminum investigations. One part attempted to determine if unit weight and cost predictions could be made by knowing the relationship of variables between a previously plotted material and a new material. Another part of the investigation found an "optimum" frame spacing for a Mariner hull built entirely of aluminum.

Definition of Semi-Aluminum Materials

The first objective was accomplished by devising a matrix of different combinations of weights, costs of materials and fabrication cost ratios. When making this series of computer runs the following properties were kept constant:

a. All stresses were based on aluminum properties; $\sigma_y = 19{,}000$ (psi), $\sigma_{ult} = 35{,}000$ (psi)

b. Modulus of elasticity, 10×10^6 (psi) and Poisson ratio, 0.33, of aluminum were used.

Table 2 shows the combinations of variables used to make up the eight "Semi-Aluminum" materials.

Table 2 Semi-Aluminum Materials' Properties

	Heavy (H)	Light (L)
1)	γ_s, c_s, f_s	γ_a, c_s, f_s
2)	γ_s, c_s, f_a	γ_a, c_s, f_a
3)	γ_s, c_a, f_s	γ_a, c_a, f_s
4)	γ_s, c_a, f_a	γ_a, c_a, f_a

where: γ_s = weight of steel

γ_a = weight of aluminum

c_s = cost of steel

c_a = cost of aluminum

f_s = 1.0 fabrication cost ratio

f_a = 1.1 fabrication cost ratio

The computed results of the various combinations are plotted in Figure 2 and tabulated in Table 12, in Appendix 1. The prediction value of the plot is illustrated by the following:

Suppose that point 1H represents a previously plotted material (1H) with the strength limitations of aluminum and the weight and cost of steel. A "new" material (4L) is found with the same strength properties but with a weight and cost of aluminum.

The weight ratio of the new material to the old is found:

$$\frac{\gamma_n}{\gamma_o} = \frac{.096}{.283} = .339$$

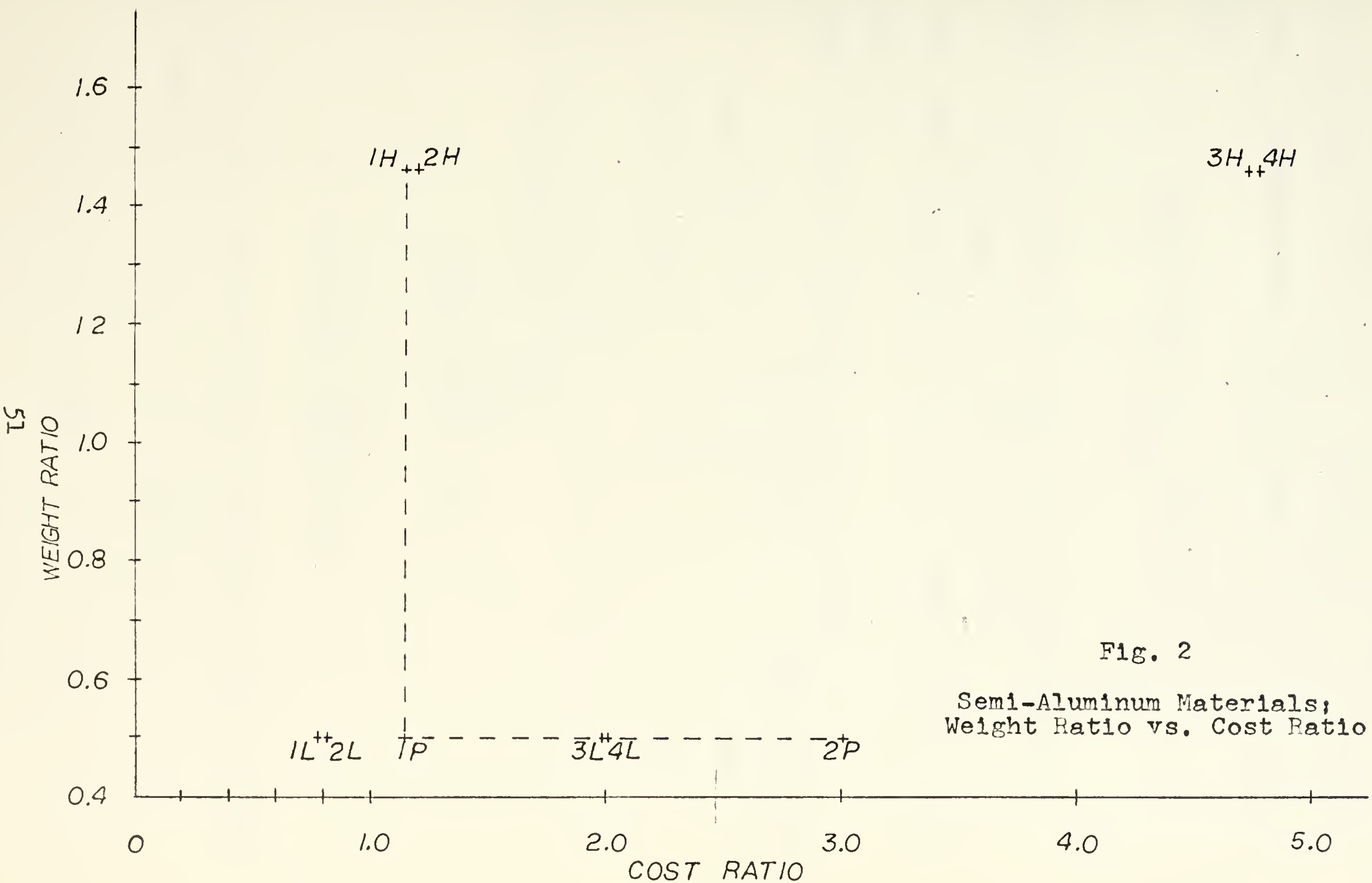

Fig. 2

Semi-Aluminum Materials; Weight Ratio vs. Cost Ratio

where: γ_n = weight of new material (lbs/in^3)

γ_o = weight of old material (lbs/in^3)

If the weight ratio of the old material is modified by this factor, the predicted weight ratio of the new material is found:

$$W_n = .339 \times W_o = .339 \times W_o$$

$$W_n = .494$$

where: W_n = predicted weight ratio of new material

W_o = weight ratio of old material

This point is projected vertically downward from 1H and is labeled 1P.

Next the ratio of material costs is found.

	"Old" (steel)	"New" (aluminum)
Plate cost	.075	.532
Stiffener cost	.075	.625

The ratio of new material cost to old material cost for plates and stiffeners is found:

$$\text{Plates } \frac{.532}{.075} = 7.09$$

$$\text{Stiffeners } \frac{.625}{.075} = 8.34$$

Assuming that 75% of the hull weight is plates and 25% is stiffeners:

An adjusted cost ratio for new to old materials is found: Material cost ratio = 7.40

In applying the cost differential ratio, it must be realized that the cost ratio includes both material cost and labor costs. Figure 3 plots the subtotal breakdown of the cost data recorded for the "hypothetical" materials discussed in Chapter V. The plot shows the relationship of labor and material costs and the total costs. Figure 4 plots the same data points; each as a percentage of the respective total cost. Figure 5 plots the subtotal breakdown of the weight data recorded for the same hypothetical materials. Tabulations of this data is found in Table 11, Appendix 1. From Figure 4 it is estimated that, for a material with a yield strength of 19,000 (psi), the labor cost is approximately 60% of the total.

Labor costs in this series of studies has been inflated by 100% to reflect overhead; in other words twice the average salary has been used to compute the labor cost. Therefore the true labor cost is approximately one third of the total cost, overhead is one third and materials make up the remaining third. In the discussion, however, the two thirds which comprise the labor costs and the overhead will collectively be called - labor costs.

Using the labor costs as 60% of the total, and considering these costs as constant the relation of the predicted

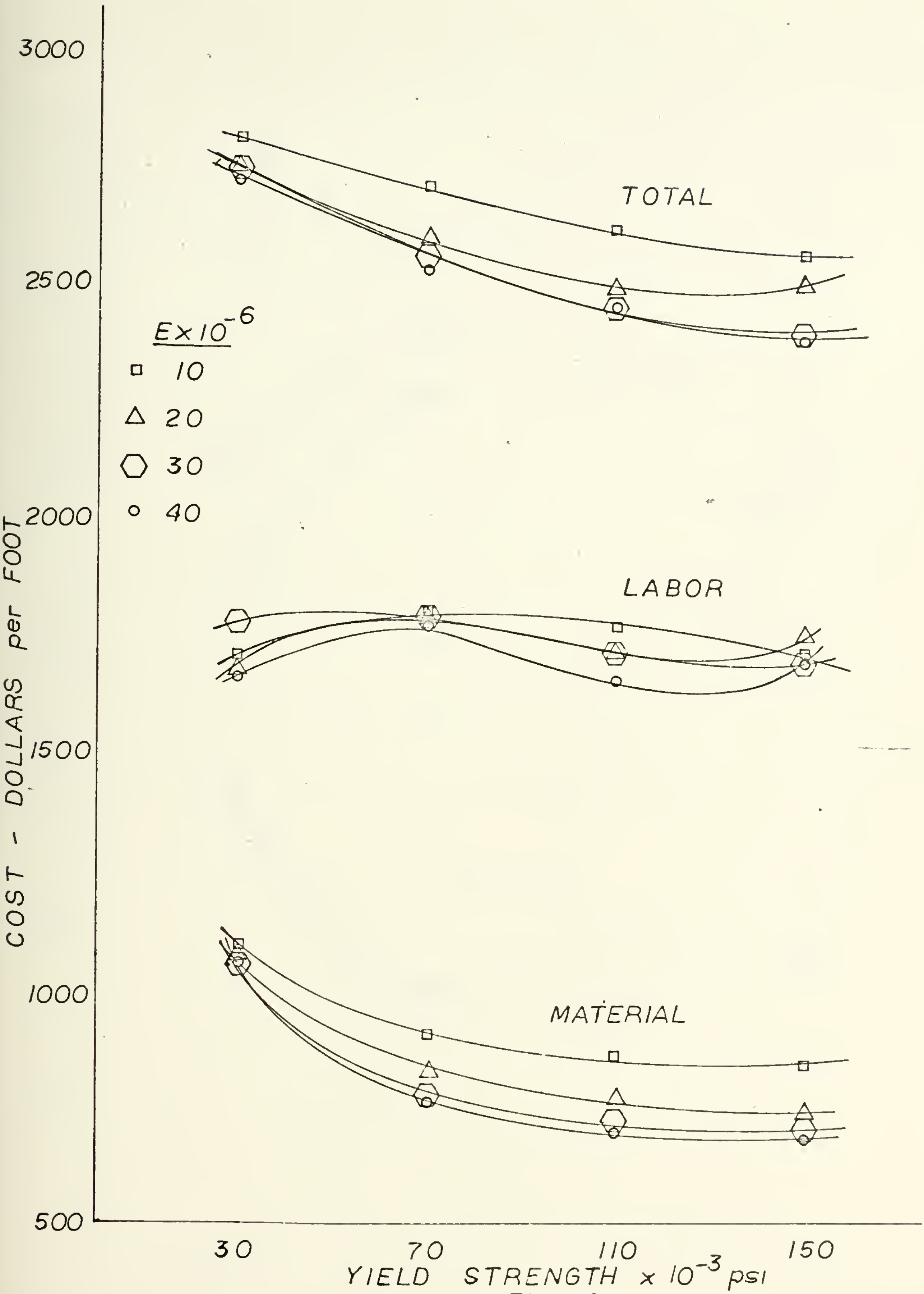

Fig. 3
Hypothetical Materials; Labor, Material and Total Costs vs. Yield Strength

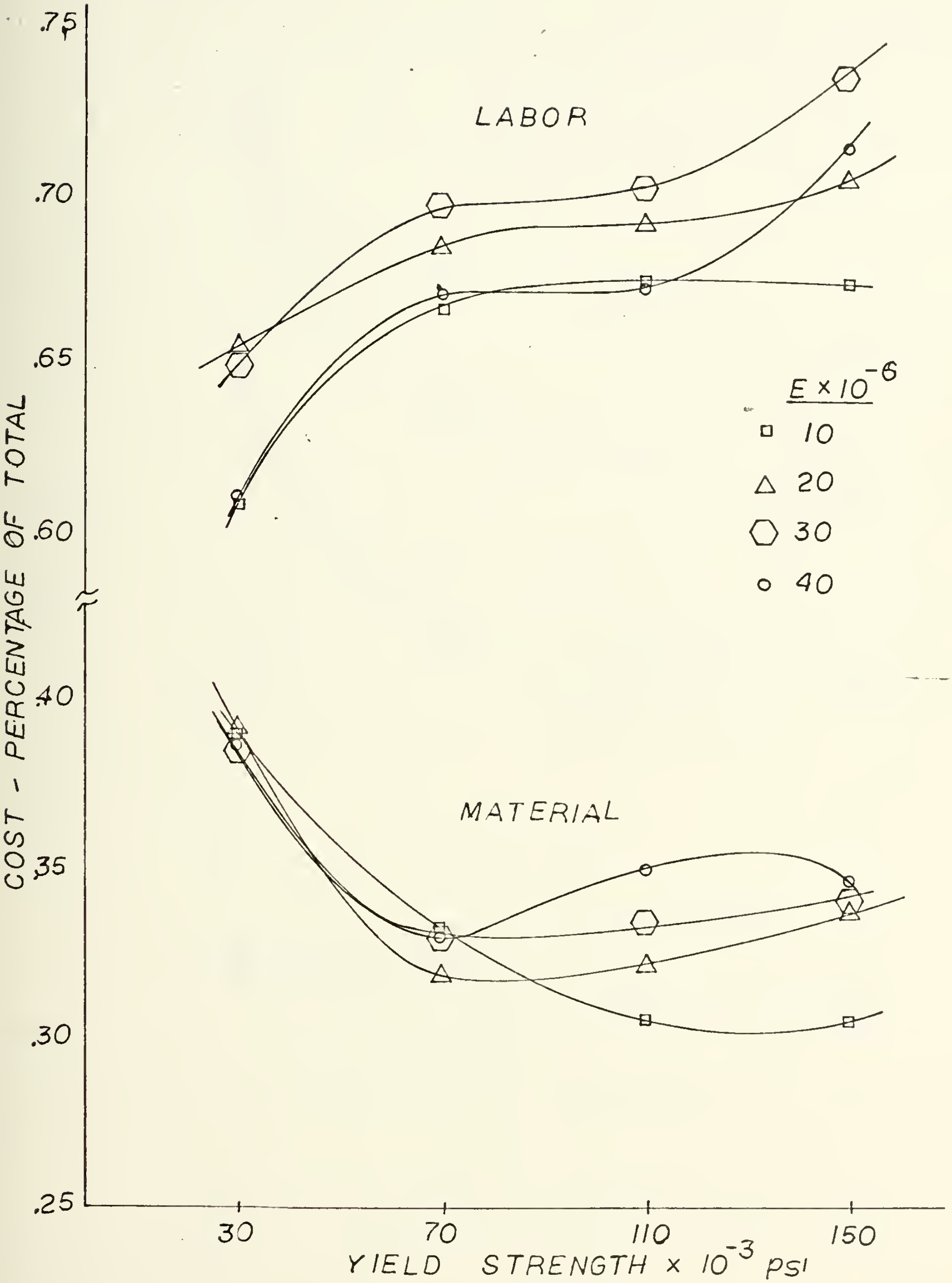

Fig. 4
Hypothetical Materials; Labor and Materials Costs as Percentage of Total Cost vs. Yield Strength

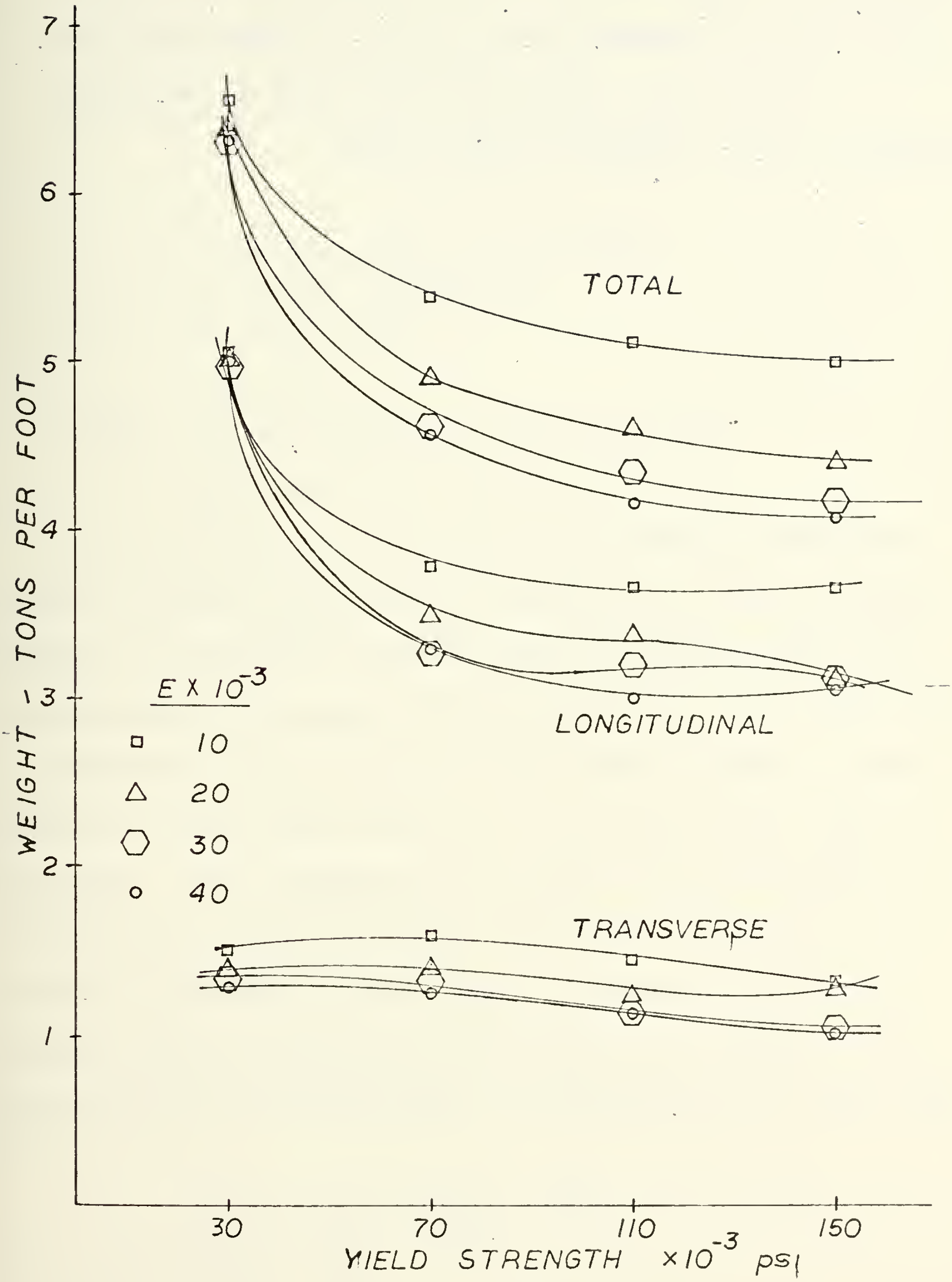

Fig. 5
Hypothetical Materials; Longitudinal, Transverse and Total Weights vs. Yield Strength

new cost to the old cost is as follows:

Labor costs = .60 x C_o (Labor costs remain constant)

Material costs = .40 x C_o (is modified by cost ratio)

Therefore: Total cost (or total cost ratio) =

Labor costs + Material costs (modified)

$$C_n = C_o(.6 + .4 \times 7.40)$$
$$C_n = 1.158(3.56)$$
$$C_n = 4.12$$

where: C_n = cost ratio of new material

C_o = cost ratio of old material

This predicts the cost ratio of point 3H with fair accuracy, however the desired prediction is for a lighter material. To correct this it must be recalled that both materials have the same allowable stresses, hence the volume of structural material will be the same for each. Since the weights are different, however, the total weight will be different. Cost figures are in terms of \$ per pound, so this difference in weight is reflected in the cost ratio. To reflect this change, 40% of the old material cost ratio, representing the material cost, should be reduced by the weight ratio of the materials. The modified old cost ratio is:

$$C_{mo} = .4 \times 1.158 \times .339 + .6 \times 1.158$$
$$C_{mo} = .157 + .695$$
$$C_{mo} = .852$$

where: C_{mo} = modified cost ratio for old material

Now using the same prediction formula as before, a cost ratio for the new light material can be found:

$$C_n = C_{mo}(.4 \times 7.40 + .6)$$

$$C_n = C_{mo}(3.56) = .852(3.56)$$

$$C_n = 3.03$$

This translates point 1P, horizontally to point 2P. This cost ratio is considerably higher than the actual light weight cost ratio (4L). By this time many errors have accumulated due to the various assumptions and approximations made. Never-the-less the predicted point does show the order of magnitude of the weight saving achieved and the cost premium paid. Refinement of the above estimates by further experimentation should produce much closer predictions.

Predictions for another material are compared with a steel performance norm curve in Figure 14, in Chapter V. Such comparisons could predict whether the new material would be competitive with steels as a ship construction material.

Aluminum Optimum Frame Spacing and Aluminum vs. Steel Economic Analysis

The second objective, that of determining the optimum frame spacing for an all aluminum hull, was accomplished by making several runs at various frame spacings. The results

are plotted in Figure 6 and tabulated in Table 14 in Appendix 1. The optimum frame spacing is 28 inches.

From this optimum an estimate can be made of the total weight and cost of the aluminum hull. The difference in total weight between a steel hull and an aluminum hull defines the extra revenue cargo that could be carried by the aluminum ship due to hull weight savings. The total cost difference defines the extra premium that must be paid for the higher cost of aluminum. To be economically attractive the aluminum hull must be able to carry enough extra revenue cargo to payoff the initial cost premium within a reasonable time, and then earn a higher profit for her owner for the remainder of the ships' life cycle.

Evans has reported - "a reasonably consistent relationship (exists) between this unit weight and the total hull steel weight (expressed as a 'prismatic weight coefficient'), at least within a particular ship type." [16] For the purpose of this brief economic analysis it will be assumed that such a relationship exists, both for steel and for aluminum. It will be further assumed that the same relationship exists between the unit cost and the total cost. The relationship assumed will be simply that the unit weight, or cost, multiplied by the vessel length will produce the total weight, or total cost, respectively. Many arguments can be immediately advanced against each of these broad assumptions. The author

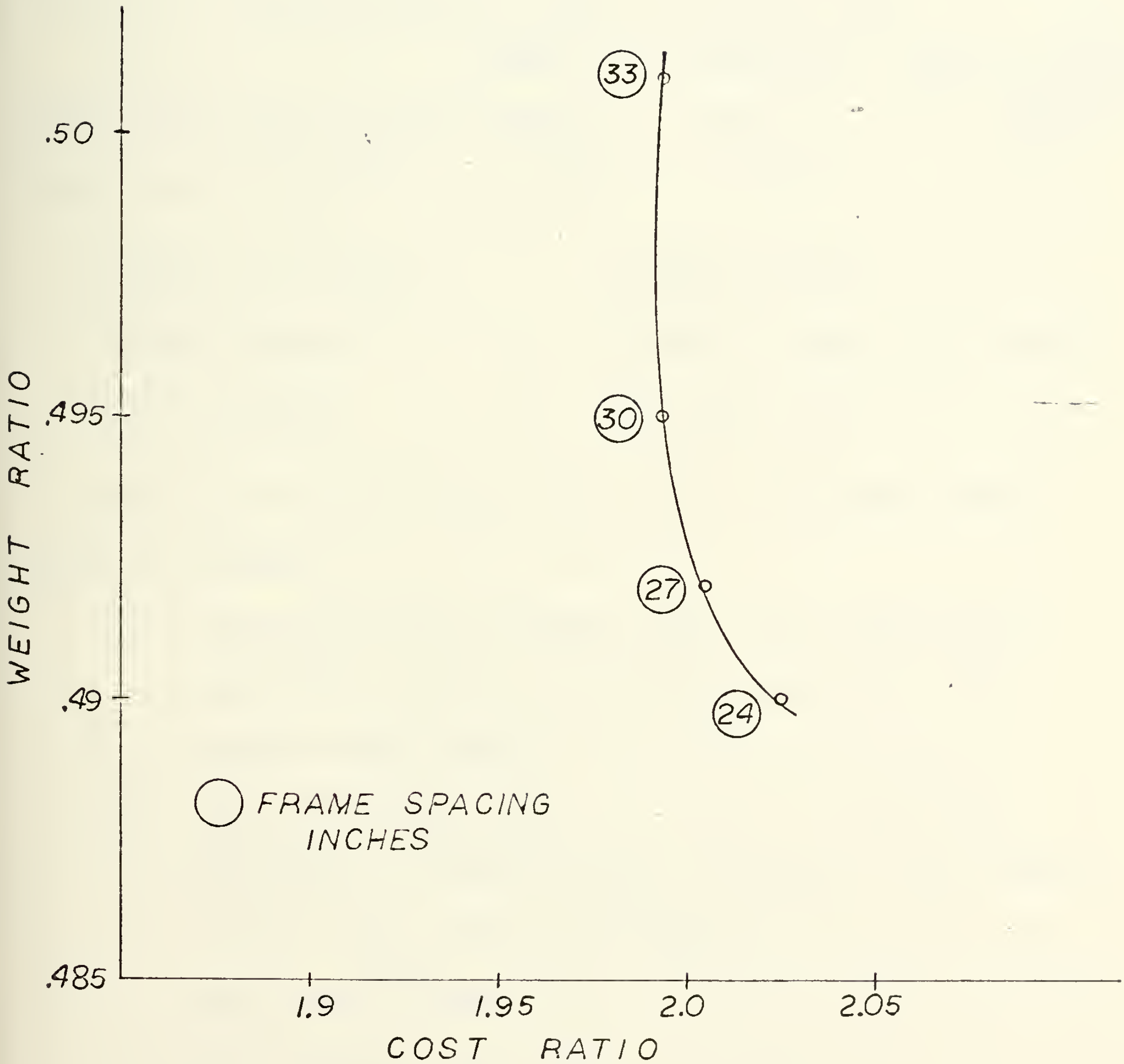

Fig. 6

Aluminum; Weight Ratio vs. Cost Ratio

is satisfied with only the first; a relationship between unit weight and total hull weight, and even here it is not suggested that the relationship is actually as simple as the one assumed. Such simple assumptions will serve however to illustrate the point.

Using the above assumptions, the following figures are found:

Mariner hull length L = 528.5 (ft)

	Steel	Aluminum	Ratio $\frac{\text{Steel}}{\text{Aluminum}}$
Total Hull Weight (tons)	3295.73	1622.50	2.03
Total cost ($\$ \times 10^{-6}$)	1.4208	2.8358	0.501

Weight Difference	1673.23 (tons)
Weight Savings	50.8% of steel hull weight
Cost Premium	$\$1.4150 \times 10^6$

For the Mariner class vessel, the following yearly cycle is assumed:

1) One round trip (assumed 3000 mile voyage) per month for a total of 12 round trips per year, and 24 cargo trips.
2) Carry cargo both ways; in order to take full advantage of weight saved, consider fully loaded on all trips. This assumption is very bad for this kind of cargo ship but makes good sense for bulk carrier types (one way only)
3) Cargo Freight rate of \$30 per ton.

Increased Revenue Per Year (IRPY) = Number of trips x Increased tonnage per trip x Freight rate per ton

$$\text{IRPY} = 24 \times 1673.23 \times 30$$
$$= \$1.2047 \times 10^6$$

Thus, with the very questionable assumptions made, the total aluminum construction premium could be recovered within 1.09 years.

This very naive economic analysis is based on the following properties for aluminum:

Yield strength (psi)	19,000
Ultimate strength (psi)	35,000
Modulus of elasticity (psi)	10×10^6
Poisson ratio	0.33
Weight (pounds per cubic inch)	0.096
Fabrication cost ratio (same fabrication costs as steel)	1.0
Cost of plates (per pound)	$0.532
Sizes: Thickness range: 0.75-0.25 inches; Length range: 72-240, 240-360, 360-480,480-612 inches; Width range: 60-80, 80-132 inches.	
Cost of stiffeners (per pound)	$0.625
Sizes: Weighted average of circle sizes 6-8, 8-10 and 10-12 inches, on a 20-40-40% basis, respectively.	

These properties are roughly representative of the aluminum alloy 5086, one of the most commonly used alloys in aluminum marine construction.

The value of 19,000 (psi) used for yield strength is based on an average of the present data available on as welded strengths of both plate and stiffener shapes. This 19,000 (psi) is considerably lower than the "advertised" yield strengths of some of the heat-treatable alloys, however these alloys have not yet been used extensively for marine structures.

The reduction in total hull weight, as a percentage of the steel hull weight, agrees very closely with other studies. MacIntyre, in a paper concerning ore carriers [5], reported that the aluminum hull weight was 56% of the weight of the steel hull; or a weight savings of 44% of the steel hull weight. Approximate calculations based on MacIntyres' paper [5] indicates that one of his aluminum ore carriers would repay the construction cost premium in about 12 years. The costs quoted in [5] are from bids on the designs.

CHAPTER V

HYPOTHETICAL MATERIALS INVESTIGATION

Definition of "Hypothetical Materials"

As mentioned earlier one series of investigations concerned hypothetical materials. The materials were "constructed" by varying the modulus of elasticity (E) over the range from 10 x 10^6 (psi) to 40 x 10^6 (psi) in steps of 10 x 10^6 (psi) while yield strength (σ_y) varied from 30 x 10^3 (psi) to 150 x 10^3 (psi) in steps of 40 x 10^3 (psi). One combination of these two properties, σ_y = 30 x 10^3 (psi) and E = 30 x 10^6 (psi), is very close to the values for medium steels. The other fifteen possible combinations do not represent any real material.

Throughout this paper the various "hypothetical materials" will be referred to by their yield strength value, σ_y times 10^{-3}, over their modulus of elasticity, E times 10^{-6}. Therefore the material with yield strength equal to 70 x 10^3 (psi) and modulus of elasticity equal to 40 x 10^6 (psi) will be called 70/40. The name is always

$$\frac{\sigma_y \times 10^{-3}}{E \times 10^{-6}}.$$

Table 3 Matrix of Hypothetical Materials (σ_y/E)

σ_y/E	10×10^6	20×10^6	30×10^6	40×10^6
30×10^3	30/10	30/20	30/30	30/40
70×10^3	70/10	70/20	70/30	70/40
110×10^3	110/10	110/20	110/30	110/40
150×10^3	150/10	150/20	150/30	150/40

These hypothetical combinations of modulus of elasticity and yield strength were investigated with two main objectives. First, and most logical, they would exercise the modified program in handling variations of E and σ_y. Second, it was anticipated that, once an optimum frame spacing was obtained for each trial "material," a grid could be plotted which would enable a prediction of the optimum spacing to be made. More important, since a previous study had delineated an attainable limit curve, or performance norm, for steels, (least weight, least cost studies for various steel combinations: Reference [16])the same grid could predict whether the new material could be competitive with the steels. If certain frame spacings resulted in plots below the steel limit curve then the new material could be considered competitive with steels. See Figure 14.

All plots are a non-dimensionalized, weight per foot ratio versus a non-dimensionalized, cost per foot ratio. The basis for the ratio is, in all cases, the weight per foot

and cost per foot for the Mariner all medium steel hull, transversely framed, and with a frame spacing of 2.5 feet. Subsequent results are divided by these base values (6.236 tons per foot and 2684.7 dollars per foot) to form the ratio for plotting.

Determination of Trial Frame Spacings

In order to plan the frame spacings to be used in the search for the optimum spacing, several attempts were made to estimate optimum spacing.

First from Sezawa:

$$\sigma_{cr} = \frac{K\pi^2 E t^2}{12(1-\lambda^2)\ a^2} \approx \sigma_y$$

Then: $$\frac{a}{t} = \left[\frac{K\pi^2 E}{12(1-\lambda^2)\ \sigma_y}\right]^{\frac{1}{2}}$$

Assuming: $\lambda \approx .3$ for all metals

For simple supports

$K = 1$

$$\frac{a}{t} = 0.95 \left[\frac{E}{\sigma_y}\right]^{\frac{1}{2}}$$

For clamped supports

$K = 4$

$$\frac{a}{t} = 1.90 \left[\frac{E}{\sigma_y}\right]^{\frac{1}{2}}$$

Using $\frac{a}{t} \approx 1.0 \left[\frac{E}{\sigma_y}\right]^{\frac{1}{2}}$ the following table can be generated.

Table 4

Optimum Frame Spacing to Plate Thickness Ratio (a/t)

σ_y/E	10×10^6	20×10^6	30×10^6	40×10^6
30×10^3	18.25	25.85	31.65	36.50
70×10^3	11.95	16.90	20.70	23.95
110×10^3	9.55	13.50	16.50	19.10
150×10^3	8.15	11.55	14.10	16.30

By making some reasonable assumptions about what percentage various locations contribute to the section modulus, a relationship for t (thickness of plating) was found:

$$t \propto \frac{1}{\sigma_y}$$

Actual Mariner deck (t_D) and bottom shell (t_S) thickness are $t_D = 1.12$ (in) and $t_S = 0.815$ (in). If these figures are taken for the $\sigma_y = 30 \times 10^3$ materials and the other materials are ratioed accordingly, two similar tables of frame spacings may be generated from Table 4, one based on t_D and one based on t_S.

Table 5 Ratioed Plating Thicknesses

σ_y (psi)	t_D (in)	t_S (in)
30×10^3	1.12	0.815
70×10^3	0.48	0.35
110×10^3	0.305	0.222
150×10^3	0.224	0.163

Table 6

Frame Spacing Based on t_S (in)

σ_y/E	10×10^6	20×10^6	30×10^6	40×10^6
30×10^3	14.85	21.00	25.80	29.60
70×10^3	4.19	5.91	7.26	8.39
110×10^3	2.12	3.00	3.66	4.25
150×10^3	1.32	1.88	2.30	2.65

Table 7

Frame Spacing Based on t_D (in)

30×10^3	20.50	29.00	35.50	40.90
70×10^3	5.73	8.11	9.98	11.48
110×10^3	2.91	4.11	5.01	5.81
150×10^3	1.82	2.59	3.15	3.65

The Mariner, as constructed of medium steel, used a frame spacing of 30 (in), about half way between the two frame spacings shown in the Tables above, based on t_S and t_D.

Since the tables above yielded such small values of frame spacing for the high yield strength materials, it was considered not feasible to use these directly. The points were plotted, however; and the shape of the curves was used, along with the knowledge that the optimum frame spacing for 32/30 steels in other studies was about 30 inches, to obtain the prediction below: (The predictions are written above the slash.)

Table 8

Estimates of Frame Spacings (in)

(from curve shape of Tables 6 and 7)

σ_y/E	10×10^6	20×10^6	30×10^6	40×10^6
30×10^3	17.5/18	25/25	30/30	35/33
70×10^3	10/9	18/18	23/24	28/27
110×10^3	8.5/9	16/15	22/21	26/25
150×10^3	7.5/9	15/15	21/21	25/25

In the interest of running as many runs as possible without changing frame spacings, these numbers were later rounded up or down to consolidate as much as possible. The numbers shown under the slash are those run as the center frame spacing, with one spacing three inches above and below the center spacing, making up a total of 48 trial runs in the first data set.

In retrospect it probably would have been better to start at 30" and drop 5" at a time, for better consolidation of frame space groupings. Second and third data sets became necessary, since the frame spacings below 15" were not particularly useful. In attempting to predict some starting point, possibly more data runs were made than would have been necessary if 30" were tried for all materials and then 5" changes were made for all materials. Figure 11 shows that what were finally defined as the optimum frame spacings vary only from 19-28 inches.

Definition of Optimum Frame Spacing

A word should be said about this "optimum" frame spacing that has been used so glibly. When the plots were first prepared and the curves seen for the first time, it became apparent that no definition could be found to define a true optimum frame spacing.

One feels inherently, or at least the author does, that the optimum must be the least weight solution that is also the least cost solution. This feeling has no rational explanation to back it up however. One ship owner with a specific problem may demand the least weight solution at a sacrifice in cost premium. Another owner may desire the least cost solution and sacrifice some weight (cargo) capacity.

Another factor complicates this optimum determination. At the time that the E and σ_y values are being varied over the range of the matrix all the other "variables" of these hypothetical materials are being held constant. (Except that allowable stresses vary with σ_y) This means that the density and the cost especially are being held constant at medium steel values. The decreases in weight per foot then become only a reflection of the reduction in the size of scantlings. And the cost ratios within a σ_y family are almost constant for each frame spacing. See Figures 7, 8, 9 and 10; plots of the hypothetical materials results in families, by yield strength. Since the cost of materials has been set constant

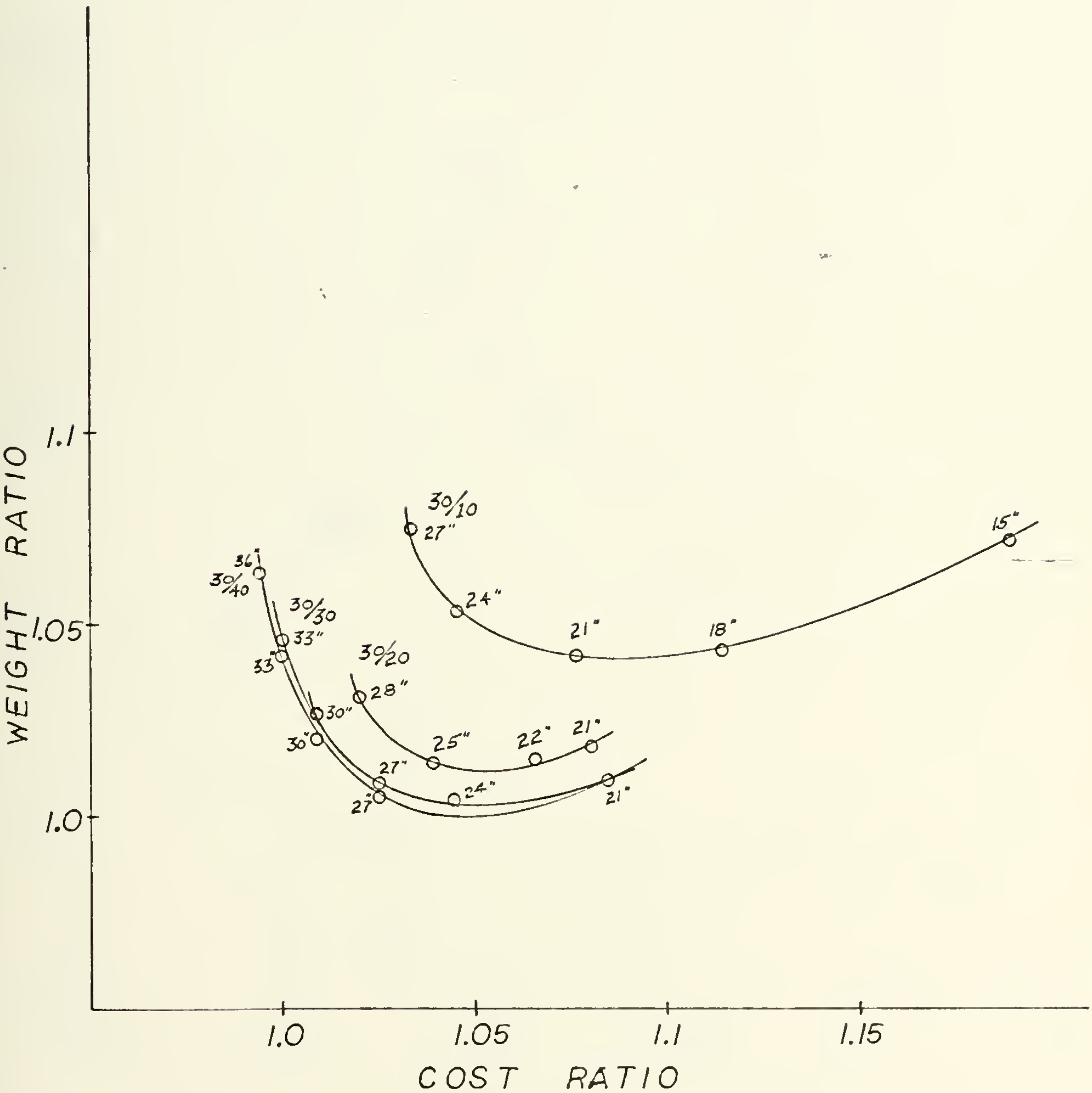

Fig. 7

Hypothetical Materials; Weight Ratio vs. Cost Ratio, Yield Strength = 30×10^3 (psi)

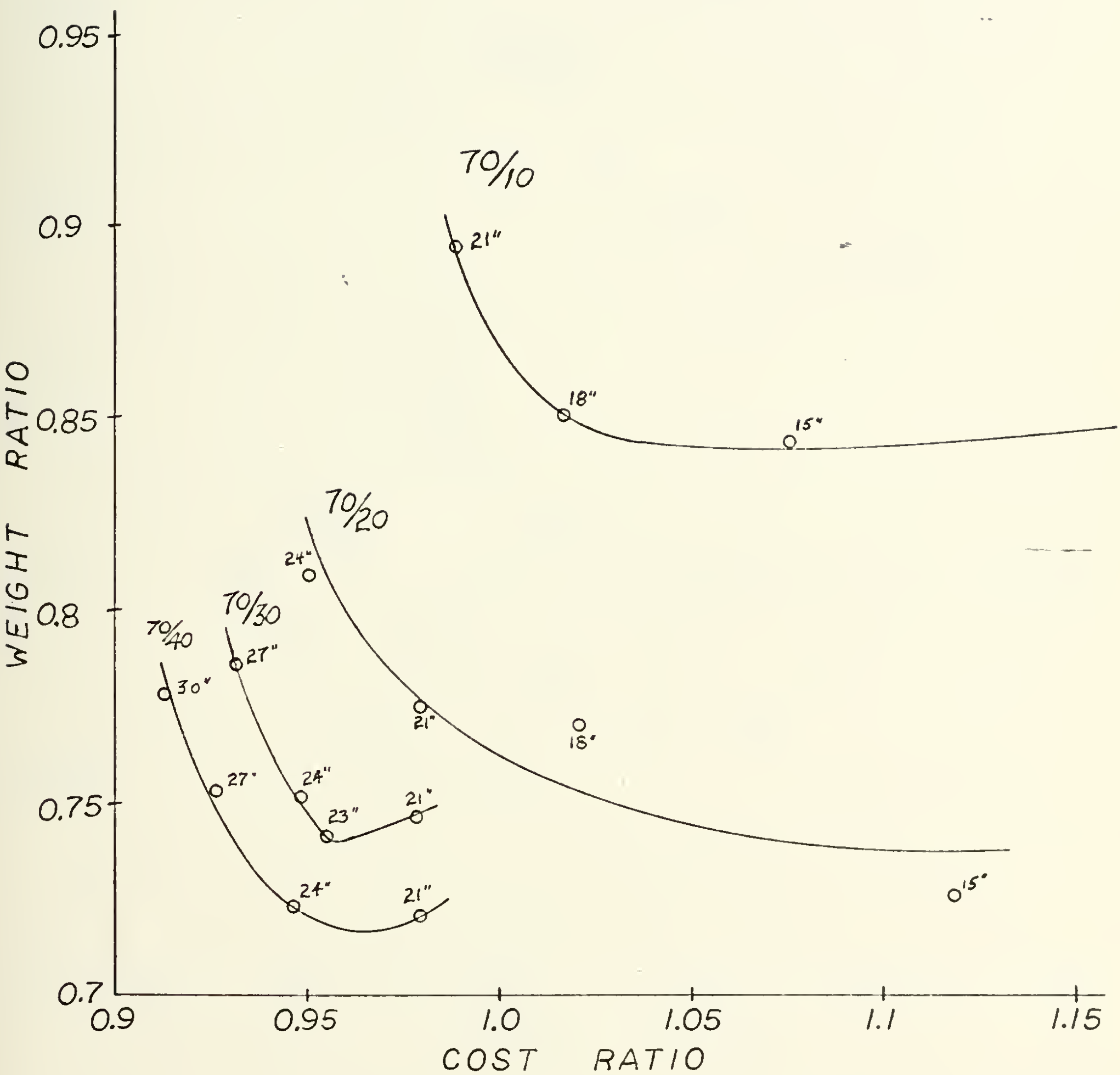

Fig. 8

Hypothetical Materials;
Weight Ratio vs. Cost Ratio,
Yield Strength = 70 x 10^3 (psi)

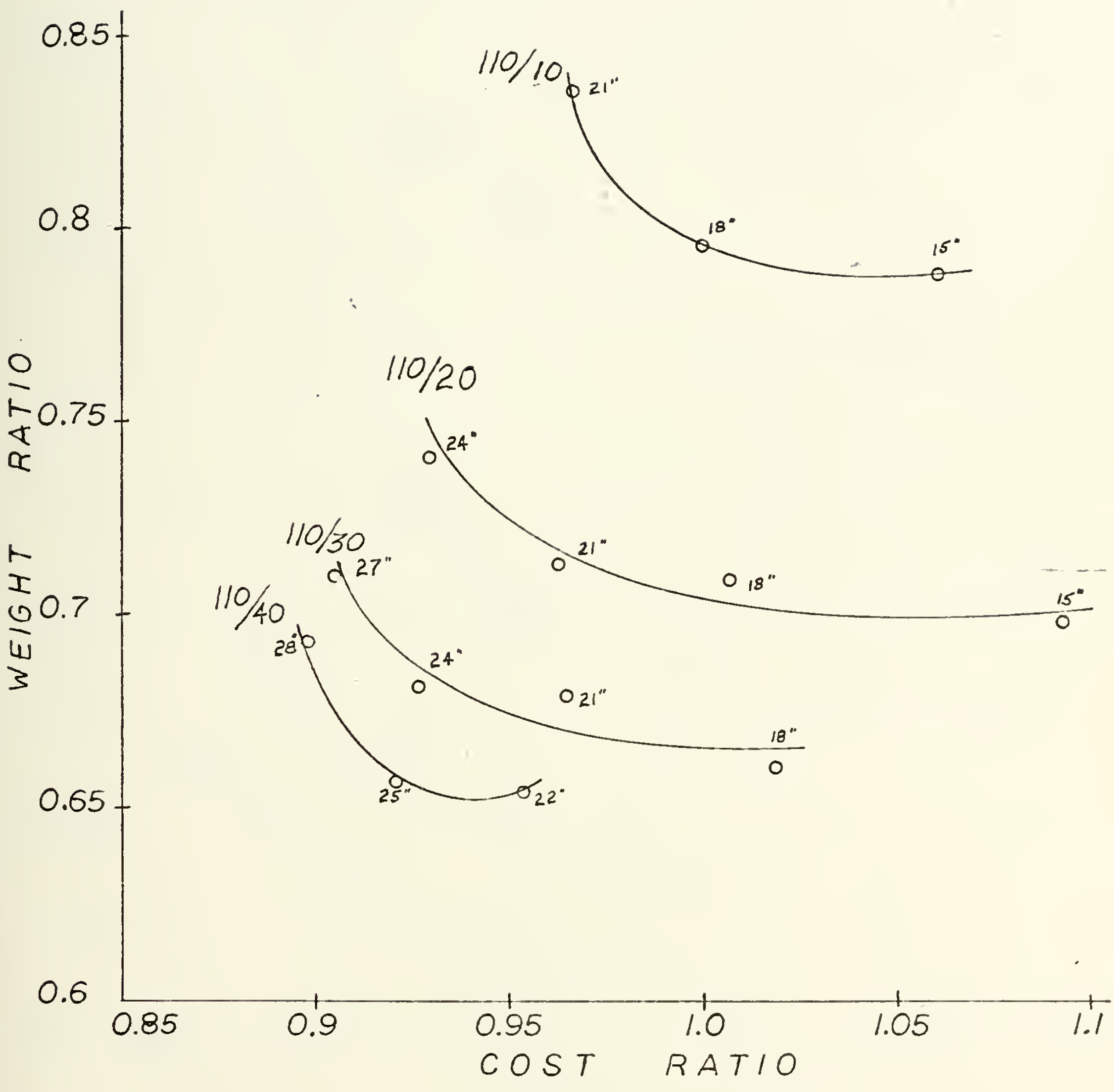

Fig. 9

Hypothetical Materials;
Weight Ratio vs. Cost Ratio,
Yield Strength = 110 x 10^3 (psi)

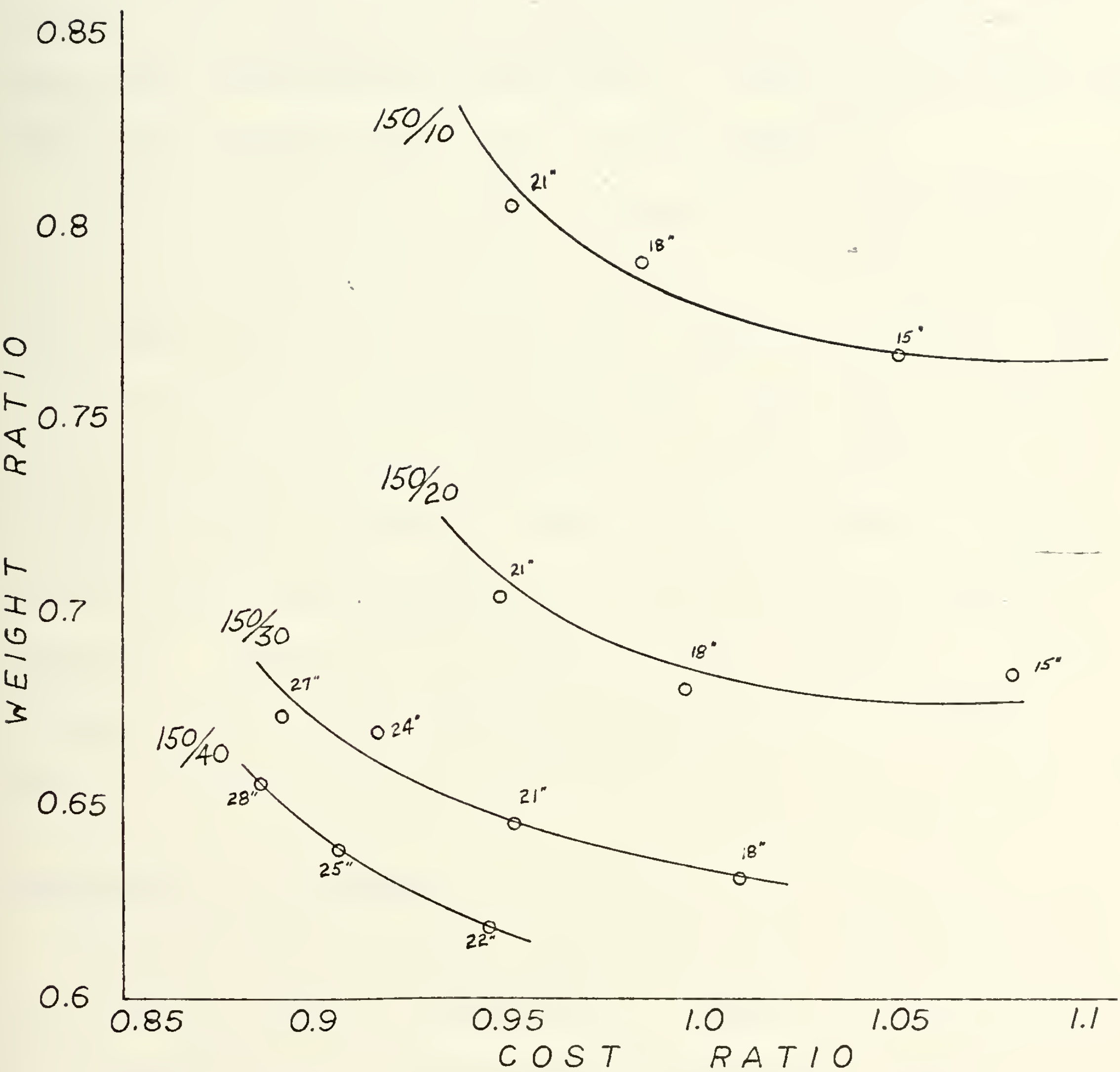

Fig. 10

Hypothetical Materials;
Weight Ratio vs. Cost Ratio,
Yield Strength = 150×10^3 (psi)

at the cost for medium steel, the cost ratio changes also reflect mainly the scantling reductions.

When one considers the density and material costs held constant as above, it appears that the plot of weight ratio versus cost ratio really reflects only weight. The fact of material costs being held constant seems to effectively de-couple the cost-weight relationship. This suggests that possibly the optimum is the least weight solution.

Never-the-less the author decided to locate the "optimum," by definition for the purposes of this paper, at that point where the slope of the curve equals 45 degrees. This has some sense of indicating that the least cost solution is of the same relative importance, to the ship owner, as the least weight solution. Table 10 in Appendix 1, shows the "optimum" frame spacing for each of the hypothetical materials. Figure 11 is a plot of these optimums - yield strength versus frame spacing, in families of constant modulus of elasticity.

Presentation of Results

Figures 12 and 13 are plots of common frame spacings of 21 and 24 inches, respectively. Figure 14 is composed of the combination of all hypothetical materials results, (Figures 7, 8, 9 and 10) with Figure 12 superimposed. Another set of prediction points, similar to those of Figure 2 are also superimposed on Figure 14.

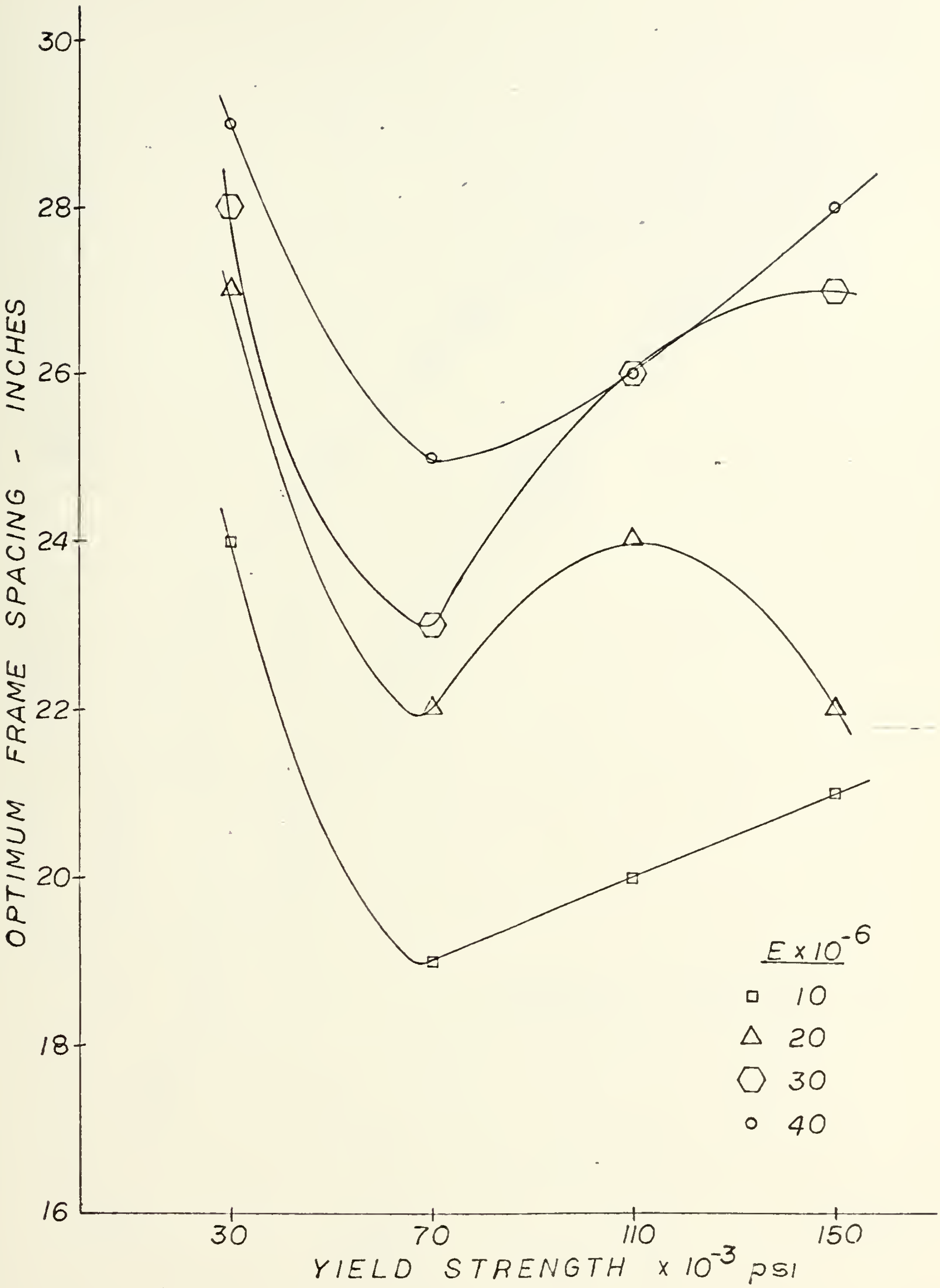

Fig. 11

Hypothetical Materials;
Optimum Frame Spacing vs. Yield Strength

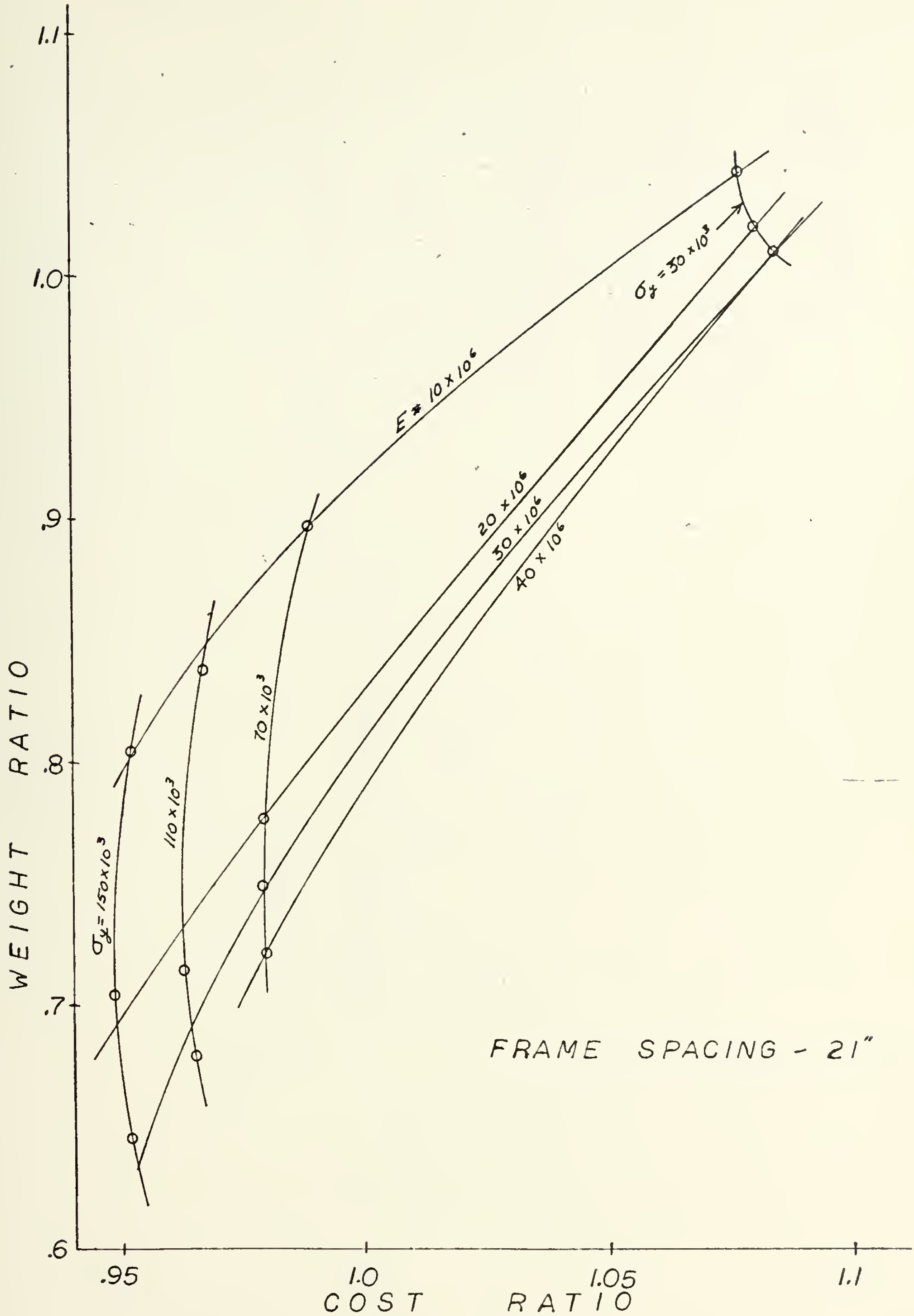

Fig. 12

Hypothetical Materials; Weight Ratio vs. Cost Ratio, 21" Frame Spacing

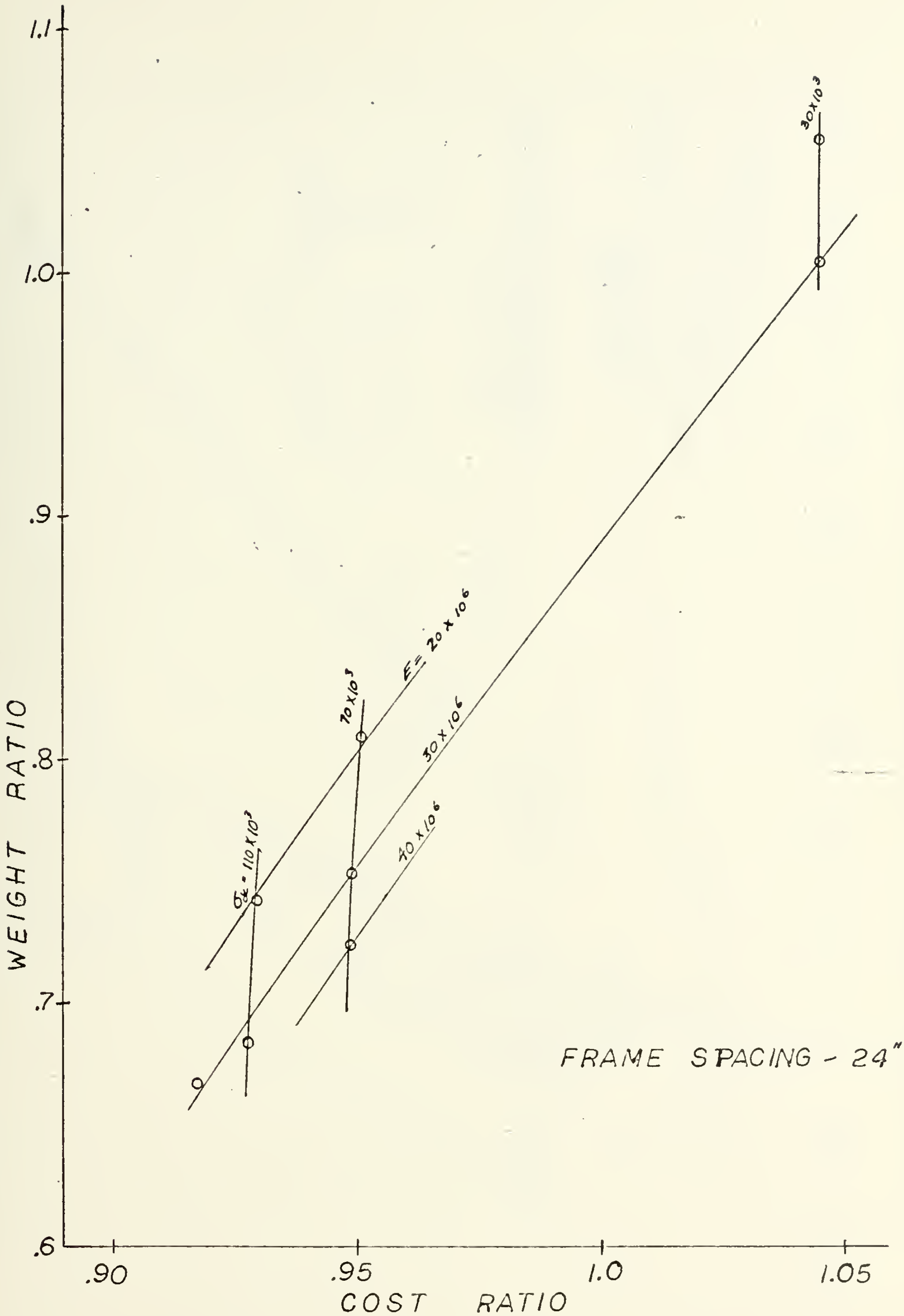

Fig. 13

Hypothetical Materials; Weight Ratio vs. Cost Ratio, 24" Frame Spacing

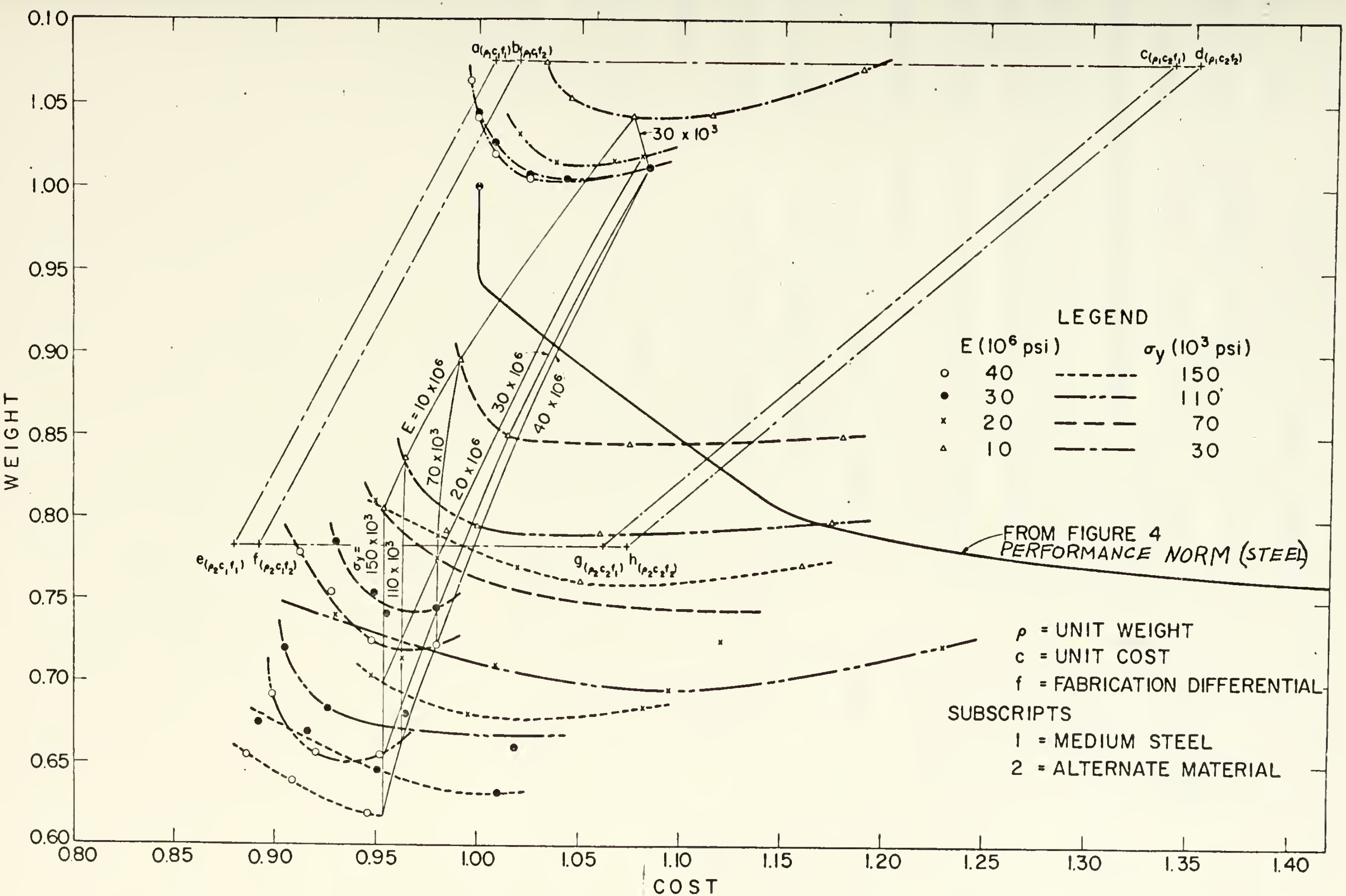

Fig. 14 - Hypothetical Materials; Weight Ratio vs. Cost Ratio, with Steel Performance Norm and Figure 12 Superimposed

Figure 14 also shows a steel performance norm curve. This curve is the result of the studies of Reference [16] and later studies and was constructed by connecting tangents to Weight Ratio vs. Cost Ratio curves for steel vessels. These curves reflected real materials with real costs and real fabrication ratio estimates. As such, their results forced the tailing-off, of the norm curve, downward and to the right, as yield strengths increased. This reflects the decreasing weights due to the higher yield strengths and also the increasing costs of such high strength materials. The results of the hypothetical materials do not show this "tailing-off" tendency because all material costs and fabrication ratios for all materials was kept constant. Every indication for real materials, to date, points toward having to "pay" a premium in cost for increased yield strength. This would cause "real" results to conform more closely the performance norm.

CHAPTER VI

DISCUSSION AND FUTURE RECOMMENDATIONS

General Comments

The results of this thesis have been discussed in the various chapters where the detailed explanation of the various investigations was presented. This section will not recap those discussions. Instead this section will discuss three main areas: Mistakes made, Computer program documentation, and Recommended future studies.

The author believes that lack of discussion of what went wrong is a major stort-coming of most theses. Another shortcoming of most computer oriented theses is the program documentation.

Mistakes Made Along the Way

Most theses expound, some at great length, on the successes achieved. Very few mention the failures that occurred along the way. The author believes this to be a great waste of valuable lessons learned.

Many mistakes were made in handling the computer runs for this thesis. First and foremost, any handling of a computer program, consisting of 75 subroutines and over 6000 Fortran cards, with data cards included, is bound to result in a few errors just from size alone; to say nothing of attempting to modify such a program. Several runs were complete

busts because of personnel handling errors at the computation facility. Several runs were encountered, where more than one error was "reported" by the compiler and not all were found and corrected by the author - thus two error runs resulted instead of the one.

This program is too LARGE to fit the WATFOR compiler - learned the hard way, but money was refunded.

Two limitations have been found in the present version of the program. These are mentioned as recommended future studies, also.

Reference [16] used version 5 of this program to design both longitudinally framed and transversely framed, as well as combination or mixed framed ships. Version 6 was found to enter an unexplained infinite loop whenever any longitudinally framed section was attempted.

A second looping instance occurs when the frame spacing is increased beyond 3.0 feet. This has occurred at 3.25 and 3.5 feet for real material properties and for hypothetical materials.

It is strongly recommended that the program be run from a compiled binary object deck. (this amounts to a reduction to about 3000 cards) Even better would be storage on data cells, disk or tape depending on the computer system being used.

Computer Program Documentations - Not What They Should Be

As mentioned in Chapter III, the author believes that what presently passes for program documentation is next to useless. The uselessness of the diagrams and flow charts, that usually are called documentation, can be forcefully shown by examining the output of the AUTOFLOW routine now available. This computer routine takes any program or subroutine source deck and diagrams it - or "documents it", if you prefer. Such "documentation" is pretty but little more useful than the Fortran listing itself.

The author recommends that meaningful documentation, useful to the user who follows the programmer, be made a requirement for all computer programs. Appendix 2 is an example of what the author believes is the documentation needed; absolutely needed, by the user who wishes to modify a program. The longer the program the greater is this need.

The user who must modify a program, (and this occurs how often at a University?), needs to know what each variable is - not what kind of a diagram is used to show a DO LOOP. He needs to know what are the outputs of each subroutine and what are the calling/called interrelations between the various program and subroutine levels. Most of all any user needs an accurate, detailed and fully descriptive set of directions for preparation of input data.

It should be acknowledged that most of the work of the directions for data input for this program was done previously and only modified here.

Recommendations for Future Studies

The first recommendation is rather obvious after reading the Mistakes Made section. Investigate and fix the looping problems concerned with longitudinal framing and with frame spacings over 3.0 feet.

Another hypothetical materials study should be conducted using constant, but realistic, costs for each group of equal high yield strength. This should cause the plots of weight ratio versus cost ratio to "tail-off", as the steel performance norm curve does. It would also show much more explicitly the effect of changing the modulus of elasticity, since presumably some curves would fall above, and some below, the performance curve.

Further studies are also needed to perfect the prediction techniques attempted here.

APPENDIX 1

This appendix contains tabulated results of the various studies conducted.

Table 9
TABULATED HYPOTHETICAL MATERIAL RESULTS

YIELD STRENGTH (X10-3PSI)	MODULUS OF ELASTICITY (X10-6PSI)	FRAME SPACING (INCHES)	TOTAL WEIGHT (TONS/FT)	WEIGHT RATIO	TOTAL COST ($/FT)	COST RATIO
30	10	15	6.693	1.072	3189.8	1.188
30	10	18	6.514	1.043	2990.3	1.114
30	10	21	6.50	1.042	2888.0	1.076
30	10	24	6.565	1.053	2806.5	1.045
30	10	27	6.699	1.074	2775.7	1.033
30	20	21	6.35	1.018	2899.8	1.080
30	20	22	6.329	1.015	2681.9	1.066
30	20	25	6.325	1.014	2786.4	1.038
30	20	28	6.434	1.031	2737.7	1.020
30	30	21	6.31	1.009	2909.2	1.084
30	30	24	6.255	1.004	2803.1	1.044
30	30	27	6.289	1.008	2754.8	1.025
30	30	30	6.402	1.027	2706.5	1.008
30	30	33	6.517	1.045	2685.0	1.000
30	40	21	6.31	1.009	2911.4	1.084
30	40	27	6.269	1.005	2756.6	1.025
30	40	30	6.362	1.020	2706.2	1.008
30	40	33	6.497	1.042	2684.0	1.000
30	40	36	6.632	1.063	2669.9	0.994
70	10	6	6.72	1.077	5289.9	1.970
70	10	9	5.447	0.873	3947.6	1.470
70	10	12	5.293	0.849	3171.0	1.181
70	10	15	5.257	0.844	2892.1	1.076
70	10	18	5.30	0.851	2732.8	1.017
70	10	21	5.574	0.895	2651.0	0.988
70	20	15	4.527	0.726	3002.3	1.118
70	20	18	4.80	0.770	2740.3	1.021
70	20	21	4.834	0.775	2628.6	0.979
70	20	24	5.045	0.809	2556.1	0.951

Table 9 (Continued)

YIELD STRENGTH (X10-3PSI)	MODULUS OF ELASTICITY (X10-6PSI)	FRAME SPACING (INCHES)	TOTAL WEIGHT (TONS/FT)	WEIGHT RATIO	TOTAL COST ($/FT)	COST RATIO
70	30	21	4.664	0.747	2626.0	0.978
70	30	23	4.625	0.742	2562.6	0.955
70	30	24	4.685	0.752	2544.0	0.948
70	30	27	4.901	0.786	2500.3	0.932
70	40	21	4.494	0.721	2630.9	0.979
70	40	24	4.505	0.723	2541.4	0.947
70	40	27	4.691	0.753	2488.8	0.927
70	40	30	4.850	0.778	2451.7	0.913
110	10	6	6.217	0.997	5301.5	1.975
110	10	9	5.243	0.841	3779.7	1.408
110	10	12	4.965	0.796	3148.7	1.174
110	10	15	4.920	0.788	2849.7	1.061
110	10	18	4.962	0.796	2683.4	1.000
110	10	21	5.207	0.836	2598.4	0.967
110	20	12	4.485	0.720	3310.9	1.232
110	20	15	4.350	0.698	2934.4	1.093
110	20	18	4.422	0.709	2703.6	1.007
110	20	21	4.457	0.713	2586.6	0.963
110	20	24	4.620	0.741	2496.4	0.929
110	30	18	4.122	0.661	2736.9	1.018
110	30	21	4.237	0.679	2590.3	0.965
110	30	24	4.250	0.682	2490.2	0.927
110	30	27	4.421	0.709	2430.4	0.905
110	40	22	4.077	0.654	2557.7	0.953
110	40	25	4.095	0.657	2472.1	0.921
110	40	28	4.323	0.693	2411.0	0.898
150	10	6	6.071	0.974	5216.6	1.943
150	10	9	5.108	0.819	3771.7	1.405
150	10	12	4.804	0.772	3114.1	1.159
150	10	15	4.778	0.767	2828.7	1.052
150	10	18	4.931	0.791	2647.2	0.985
150	10	21	5.014	0.805	2559.9	0.952

Table 9 (Continued)

YIELD STRENGTH (X10-3PSI)	MODULUS OF ELASTICITY (X10-6PSI)	FRAME SPACING (INCHES)	TOTAL WEIGHT (TONS/FT)	WEIGHT RATIO	TOTAL COST ($/FT)	COST RATIO
150	20	12	4.314	C.692	3282.6	1.222
150	20	15	4.268	C.684	2901.8	1.081
150	20	18	4.241	C.680	2675.6	0.996
150	20	21	4.374	C.703	2546.4	0.948
150	30	18	3.941	0.632	2714.1	1.01
150	30	21	4.024	0.646	2559.8	0.952
150	30	24	4.163	0.668	2461.9	0.917
150	30	27	4.196	0.673	2394.5	0.892
150	40	22	3.857	C.618	2540.2	0.946
150	40	25	3.978	0.638	2435.1	C.907
150	40	28	4.090	0.656	2377.9	0.886

Table 10
TABULATED HYPOTHETICAL MATERIAL CPTIMUM RESULTS

YIELD STRENGTH (X10-3PSI)	MODULUS OF ELASTICITY (X10-6PSI)	FRAME SPACING (INCHES)	TOTAL WEIGHT (TONS/FT)	WEIGHT RATIO	TOTAL COST ($/FT)	COST RATIO
30	10	24	6.565	1.C53	2806.6	1.045
30	20	27	6.398	1.026	2753.9	1.026
30	30	28	6.327	1.015	2738.7	1.020
30	40	29	6.344	1.017	2723.0	1.014
70	10	19	5.391	C.864	2705.5	1.008
70	2C	22	4.904	0.786	2604.76	0.97C
70	30	23	4.625	C.741	2562.6	C.954
70	4C	25	4.567	C.732	2523.9	C.94C
110	10	20	5.126	0.822	2626.5	0.978
110	20	24	4.620	0.741	2496.4	C.93C
110	30	26	4.364	C.70	2449.3	0.912
110	40	26	4.171	C.669	2451.8	0.913
150	10	21	5.014	0.804	2559.9	0.952
150	2C	22	4.418	0.708	2503.3	0.932
150	30	27	4.196	0.673	2394.5	0.892
150	40	28	4.090	0.655	2377.9	0.886

Table 11

TABULATED WEIGHT AND COST SUBTOTALS FOR HYPOTHETICAL MATERIAL OPTIMUMS

YIELD STRENGTH (X10-3PSI)	MODULUS OF ELASTICITY (X10-6PSI)	FRAME SPACING (INCHES)	WEIGHTS LONGITUDINAL (TONS/FT)	WEIGHTS TRANSVERSE (TONS/FT)	COSTS MATERIAL ($/FT)	COSTS LABOR ($/FT)
30	10	24	5.06	1.505	1098.1	1708.5
30	20	27	5.0	1.394	1070.8	1683.1
30	30	28	4.97	1.357	1059.03	1779.7
30	40	29	5.02	1.314	1059.86	1663.3
70	10	19	3.79	1.601	901.6	1803.9
70	20	22	3.493	1.411	819.86	1784.9
70	30	23	3.28	1.345	773.5	1789.1
70	40	25	3.3	1.267	763.5	1760.4
110	10	20	3.664	1.462	857.26	1769.4
110	20	24	3.39	1.230	772.9	1723.4
110	30	26	3.214	1.150	730.0	1720.5
110	40	26	3.016	1.154	697.86	1653.8
150	10	21	3.67	1.344	839.0	1720.9
150	20	22	3.14	1.279	740.23	1763.1
150	30	27	3.13	1.066	701.4	1693.1
150	40	28	3.06	1.03	684.3	1693.6

Table 12
TABULATED SEMI-ALUMINUM RESULTS

YIELD STRENGTH (X10-3PSI)	MODULUS OF ELASTICITY (X10-6PSI)	FRAME SPACING (INCHES)	TOTAL WEIGHT (TONS/FT)	WEIGHT RATIO	TOTAL COST ($/FT)	COST RATIO
19	10	30	9.087	1.457	3110.1	1.158
19	10	30	9.087	1.457	3238.1	1.206
19	10	30	9.087	1.457	12672.6	4.720
19	10	30	9.087	1.457	12800.6	4.768
19	10	30	3.084	0.495	2104.1	0.784
19	10	30	3.084	0.495	2232.2	0.831
19	10	30	3.084	0.495	5348.0	1.992
19	10	30	3.084	0.495	5476.0	2.040

Table 13
TABULATED WEIGHT AND COST SUBTOTALS FOR SEMI-ALUMINUM RESULTS

YIELD STRENGTH (X10-3PSI)	MODULUS OF ELASTICITY (X10-6PSI)	FRAME SPACING (INCHES)	WEIGHTS LONGITUDINAL (TONS/FT)	TRANSVERSE (TONS/FT)	COSTS MATERIAL ($/FT)	LABOR ($/FT)
19	10	30	7.63	1.457	1522.3	1587.7
19	10	30	7.63	1.457	1522.3	1715.8
19	10	30	7.63	1.457	11084.9	1587.7
19	10	30	7.63	1.457	11084.9	1715.8
19	10	30	2.59	0.494	516.4	1587.7
19	10	30	2.59	0.494	516.4	1715.8
19	10	30	2.59	0.494	3760.2	1587.7
19	10	30	2.59	0.494	3760.2	1715.8

Table 14
ALUMINUM RESULTS WITH OPTIMUM RESULTS

YIELD STRENGTH (X10-3PSI)	MODULUS OF ELASTICITY (X10-6PSI)	FRAME SPACING (INCHES)	TOTAL WEIGHT (TONS/FT)	WEIGHT RATIO	TOTAL COST ($/FT)	COST RATIO
19	10	24	3.055	0.490	5435.4	2.025
19	10	27	3.063	0.492	5374.5	2.005
19	10	30	3.084	0.495	5348.0	1.993
19	10	33	3.119	0.501	5351.6	1.994
ALUMINUM OPTIMUM						
19	10	28	3.07	0.492	5365.7	1.999

APPENDIX 2

This appendix contains descriptions of subroutines and their interrelations and definitions of the program variables.

Table 15
SUBROUTINE INTERRELATIONS

Subroutine	Description of Function	Output	Called by	Calls
MAIN	Executive of program - manipulates other routines			BASIC DETAIL FRAME PROMAT MATASG STRUCT TRANSV INCOST GEOMTY ASGPLT ASGSTR SETUP DESIGN TVMN COST
BASIC	Reads basic geometry	KSECT SHIP	MAIN	
DETAIL	Reads detail geometry	BHD HFHAT DKHT	MAIN	
FRAME	Fills remainder of array SHIP 9,10,11 Fills array SPCNOM - set to zero for transverse framing; otherwise modification is added or subtracted	SHIP SPCNOM	MAIN	

Subroutine	Description of Function	Output	Called by	Calls
MATASG	Reads material assignments	ZIF NIF NM ZINT	MAIN	
STRUCT	Reads moment and stress input or makes assumption Contains scantlings of "standard" stiffener	STSPAR SCANT	MAIN	SECMOD
TRANSV	Reads open/closed floor ratio and hatch length/hold length ratio Reads type of deck support number and dimensions	OFRAT HLRAT NTYP YSUP	MAIN	
ASGPLT	Assigns material type to plates	PLT(2,*,*)	MAIN	
ASGSTR	Assigns material type to stiffeners	STR(4,*,*)	MAIN	
SECMOD	Defines section modulus: by load line regs, (for LBP less than 600 ft); and by Baker's extension of load line regs, (for LBP greater than 600 ft); also adds 10% safety factor.	SECMOD	STRUCT	
INCOST	Fills 9-11 of PROPTY array, costs of materials and fabrication cost factor Reads in salary in (Dollars per man-hour)	PROPTY SALARY	MAIN	
PROMAT	Reads material properties	PROPTY (1-8) NUMUSD	MAIN	

Subroutine	Description of Function	Output	Called by	Calls
PNTPLT	Print plate coords	PRINT	GEOMTY	
PNTSTR	Print stiffener coords	PRINT	GEOMTY	
PTSTRL	Print stiffener head loads	PRINT	SETUP	
PTSMLD	Print seam head loads	PRINT	SETUP	
PNTBOT	Print bottom framing	PRINT	TVMN	
P6	Print area, moment and inertia constants	PRINT	GEOMTY	
PNTTHK	Print plate thicknesses and metal type	PRINT	DESIGN SETUP	
PNTPRP	Print stiffener scantlings and properties	PRINT	DESIGN SETUP	
PNTWT	Print transverse weight (per section)	PRINT	TVMN	
PNTDSF	Print deck and shell frame scantlings	PRINT	TVMN	
PRNTCO	Print results of cost analysis	PRINT	COST	
PNTINT	Print section inertia details	PRINT	DESIGN	
PNTSUM	Print summary of final results for each ship	PRINT	COST	
NOMNAL	Assign nominal spacing for stiffeners and define: Standard width	NSPACE WIDTH	SSPACE PLTSMS	

Subroutine	Description of Function	Output	Called by	Calls
GEOM	Computes detailed geometry at turn of bilge	CONST	GEOMTY LOADS THKLOX THKTRX TRVLAT THKTRV THKLON COST	
LENGTH	Determines lengths of sections	GIRTH	GEOMTY	BHDEND
BHDEND	Find top and bottom heights of a bulkhead	ZBOT ZTOP	YZSEAM LENGTH BHDSTR	
AMICON	Calculate area, moment and inertia constants for all plates	AMI	GEOMTY	PARABO FUNAMI
FUNAMI	Fills part of AMI(I,J,K)	AMI	AMICON	
PARABO	Fills part of AMI(I,J,K) for parabolic deck	AMI	AMICON	
BHDSTR	Space stiffeners on longitudinal bulkheads	STR	GEOMTY	BHDEND
PLTSMS	Determine girths of plate seams for each section	SEAM(1,*,*)	GEOMTY	NOMNAL
YZSEAM	Determine Y and Z seam coords	SEAM(2,*,*) (3,*,*)	GEOMTY	BHDEND
SSPACE	Fills standard width for all sections except decks Fills stiffener spacing for all sections except decks	SPACE KSTR	GEOMTY	NOMNAL

Subroutine	Description of Function	Output	Called by	Calls
DKSSTR	Fills STR(1,*,*) for all decks (2,*,*)	KSTR(I) STR(I,J,K)	GEOMTY	
GEOMTY	Calls subroutines and fills outputs.		MAIN	GEOM LENGTH SSPACE DKSSTR BHDSTR PNTSTR PLTSMS YZSEAM PNTPLT AMICON P6
LOADS	Head loads for stiffeners Head loads for plates at seams Maximum load due to either 30° heel, L/20 wave, green water head	HDSTR HDSEAM	SETUP	GEOM
PSCOM	Combined area plate and stiffeners Combined inertia plate and stiff taking N. A. shift in account Combined section modulus	COMBAR CONBIN ZMOD	STRLOX STRLON	
PLTSTR	Section index Plate index Used to find plate related to stiff, in section (IP)	IP KP	STRLOX STRLON	
ABSCON	Assigns A.B.S. constants to a stiffener	CXHD	STRLOX STRLON	

Subroutine	Description of Function	Output	Called by	Calls
STRLOX	Fills STR(3,*,*) with proportionality constant	STR(3,*,*)	SETUP	PLTSTR STRES1 PSCOM ABSCON INTERP
THKLOX	Fills PLT(1,*,*) with thickest calculated plate Defines initial longitudinal framed plate size	PLT(1,*,*)	SETUP	GEOM SHLPLT STRES1 LONLAT THKBUK
AMISTR	Fills AMITOT(1,2and3) for stiffeners	AMITOT(I)	DESIGN LINPRG	
AMIPLT	Fills AMITOT(1,2and3) for plate	AMITOT(I)	DESIGN LINPRG	
AMICVK	Fills AMITOT(1,2and3) for CVK	AMITOT(I)	DESIGN LINPRG	
STRES1	Fills initial SIG array	INITIAL SIG	STRLOX THKTRX THKLOX	
SETUP	Initiates design; by water head loads		MAIN	LOADS PTSTRL PTSMLD THKTRX THKLOX PNTTHK STRLOX PNTPRP

Subroutine	Description of Function	Output	Called by	Calls
THKTRX	Defines initial size of transversely framed plate Fills PLT(1,*,*) with max thickness plate calculated	PLT(1,*,*)	SETUP	GEOM SHLPLT STRES1 TRVLAT THKBUK
TRVLAT	Formulas for transversely framed plate under lateral load	TLAT	THKTRX THKTRV	GEOM
LONLAT	Formulas for longitudinally framed plate under lateral load	TLAT	THKLOX THKLON	
SHLPLT	Associates shell plates with a section	K1	THKLOX THKTRX THKTRV THKLON	
INTERP	Linear interpolation	TRPLIN	STRLOX STRLON THKBUK	
STRESS	Fills SIG(1,2and3)	SIG	THKTRV DESIGN LOCDEF LINPRG THKLON STRLON	
THKTRV	Fills PLT(1,*,*) with "TNEW" from AVERG TNEW is average of TOLD and new thickness on each cycle	PLT(1,*,*)	DESIGN	GEOM SHLPLT STRESS TRVLAT THKBUK AVERG

Subroutine	Description of Function	Output	Called by	Calls
THKLON	Fills PLT(1,*,*) with "TNEW" from AVERG TNEW is average of TOLD and new thickness on each cycle	PLT(1,*,*)	DESIGN	GEOM SHLPLT STRESS LONLAT THKBUK AVERG
DESIGN	Calls subroutines to design longitudinal structure		MAIN	AMISTR AMIPLT AMICVK STRESS THKLON THKTRV STRLON LINPRG PNTPRP PNTTHK PNTINT
STRLON	Defines stiffener sizes during cycling	STR(3,*,*)	DESIGN	PLTSTR STRESS PSCOM ABSCON INTERP
AVERG	Averages "TOLD" with new "T"	TNEW	THKTRV THKLON	
LINPRG	Linear program to remove stress deficiencies	LP PLT(1,*,*)	DESIGN	LOCDEF TINCRE AMISTR AMIPLT AMICVK STRESS

Subroutine	Description of Function	Output	Called by	Calls
TINCRE	Increases top and bottom plates thicknesses a given amount. Fills "NEW" PLT(1,*,*)	PLT(1,*,*)	LINPRG	
LOCDEF	Locates deficient interfaces under primary STRESS	KUP KLO SUP SLO DEF	LINPRG	STRESS
THKBUK	Formulas for buckling of PLTS, both longitudinal and transverse framing	TBUK	THKTRX THKTRV THKLON THKLOX	INTERP
TVMN	Calls subroutines to design transverse structure		MAIN	SPAN TVHEAD DKBEAM SFRAME PNTDSF BOTDES PNTBOT TVWT PNTWT
SPAN	Finds spans of transverse structural frames	TBEAM HBEAM BOTF CLFLR REVFR	TVMN	
TVHEAD	Calculates heads (from A.B.S.) on transverse structure	HDABS VLOAD	TVMN	

Subroutine	Description of Function	Output	Called by	Calls
DKBEAM	Designs transverse deck beams Fills TBEAM (2,*,*) and (3,*,*) Fills HBEAM (2,*,*) and (3,*,*)	TBEAM HBEAM	TVMN	BRAKET WEBDES
SFRAME	Designs side frames Fills TBEAM (2,*,*) and (3,*,*)	TBEAM	TVMN	BRAKET WEBDES
BOTDES	Designs bottom transverse structures	BOTF REVFR CLFLR WEB	TVMN	WEBDES
TVWT	Computes weight per linear foot for transverse structure	WT	TVMN	
BRAKET	Calculates bracket sizes for span reduction	OK BRAT	DKBEAM SFRAME	
WEBDES	Designs web frames	WEB	DKBEAM SFRAME BOTDES	
COST	Determines total labor and material costs of midship section		MAIN	GEOM CONVRT LABCOS MATCOS PRNTCO PNTSUM

Subroutine	Description of Function	Output	Called by	Calls
CONVRT	Converts index system for cost summation	APC ASC WP WS SF AP AS CWTT	COST	
LABCOS	Determines labor costs per section and total labor cost	CLAB TCLAB	COST	TIMFAC
MATCOS	Determines cost of material	CMAT	COST	
TIMFAC	Sets time factor for calculating man hours	TFAC	LABCOS	

DEFINITIONS OF VARIABLES

IDIM1 = Number of decks + 1 (for innerbottom, if one exists) + number of longitudinal bulkheads + 1 (for bottom shell) + number of side sections [IDIM1 = KSECT(7)]

IDIM2 = Number of decks + 1 (for innerbottom, if one exists) + 1 (for bottom shell) + number of longitudinal bulkheads [IDIM2 = KSECT(4) + KSECT(3)]

KDIM1 = 500 divided by IDIM1

KDIM2 = 400 divided by IDIM2

IDIM1, IDIM2, KDIM1, and KDIM2 are used to dimension arrays

I2=2, I3=3, I4=4: used as counters or indicators

KSHIP = Counter to indicate ship number being processed.

KSHIP1 = Counter to indicate ship number about to be processed

BASWT = Base weight, used to form weight ratio for summary of results. Ratio is current ship results divided by base.

BASCOS = Base cost, used to form cost ratio, as above.

KEY = Print indicator - KEY=0, print all intermediate results and summary; KEY=1, print only final plate thicknesses and summary of results.

NM = Number of material sections or horizontally divided areas that the ships depth is divided into.

NIF = NM + 1

MATRL = Material type number for all transverse structure

TMARAT = Ratio of allowable σ_2 stress for medium steel to allowable σ_2 stress for material being used for transverse structure.

EPRIE = Ratio of modulus of elasticity of material used for transverse structure to modulus of elasticity of steel.

PPPRI = Ratio of quantity $(1-\lambda^2)$ for steel to quantity $(1-\lambda^2)$ for material used for transverse structure, where λ=Poisson ratio.

OFRAT = Ratio of number of open floors to number of closed floors per hold.

HLRAT = Ratio of hatch length to hold length.

BP = Length between perpinduclars [=SHIP(1)]

B = Breadth [=SHIP(2)]

H = Draft [=SHIP(4)]

SALARY = Labor wage rate (dollars per man-hour)

NUMUSD = Number of materials read in as data to fill properties of materials array (Maximum number is 5)

NUMCOS = Number of sets of cost data read in as data. This number must match NUMUSD above.

IKEY = Indicator for printing plate thicknesses; not printed on initial cycle, printed on final cycle.

TOTCOS = Total cost per foot

NSPACE = Number of longitudinals in a given width

DIST = A given width of plate

STDWTH = Standard width of plate; set as a DATA statement in subroutine PLTSMS.

WIDTH = Spacing of longitudinals $\text{WIDTH} = \frac{\text{DIST}}{\text{NSPACE}}$

ZTOP = Height of top of longitudinal bulkhead

ZBOT = Height of botton of longitudinal bulkhead

ZMOD = Combined plate and stiffener section modulus

COMBAR = Combined area, plate and stiffener

COMBIN = Combined inertia, plate and stiffener

P = Proportionality constant

E = Effective width of a plate

T = Plate thickness

CXHD = A.B.S. modification to head

SY = Y coordinate

SZ = Z coordinate

IP = Section indicator index

KP = Plate index

MBR = Used to call material type number

S3BAR = A particular tertiary stress

S1BAR = A particular primary stress

HEAD = A particular head

TLAT = Thickness of plate required by lateral load

INDEX = A particular index

K1 = Section indicator index

K2 = Plate index

Z = Z coordinate

LP = Linear program result indicator

TOLD = Plate thickness, called old or previous

TNEW = Output of AVERG - average of TOLD and new T in cycling.

KUP = Upper interface index

KLO = Lower interface index

SUP = Stress at upper interface

SLO = Stress at lower interface

SACT = A primary stress

A = Transverse spacing

B = Spacing between seams

MAT = Material type number indicator

TBUK = Thickness required due to buckling

BRKRAT = Bracket ratio set at 0.95

BRAT = Calculated bracket ratio

OK = Indicator for bracket ratio within tolerance

ZABS = A particular section modulus

GIRVAL = A particular section modulus

DMIN = A.B.S. constant

TCLAB = Total cost of labor

TFAC = Construction time factor

DEFINITIONS OF ARRAY VARIABLES

```
SHIP      (1) = Length
          (2) = Breadth
          (3) = Depth
          (4) = Draft
          (5) = Bilge radius
          (6) = Center vertical keel (CVK) height
          (7) = Dead rise
          (8) = Camber
          (9) = Transverse spacing
         (10) = Longitudinal spacing
         (11) = Web spacing

KSECT     (1) = No. of decks
          (3) = No. of longitudinal bulkheads per ½ section
                If No Inner Bottom              If an Inner Bottom
          (2) = (1)                       (2) = (1)+1
          (4) = (2)+1=(1)+1               (4) = (2)+1=(1)+2
          (5) = 2*(1)                     (5) = (4)+(1)=2*(1)+2
          (6) = (5)+1=2*(1)+1             (6) = (5)+1=2*(1)+2
          (7) = (5)+(3)=2*(1)+(3)         (7) = (5)+(3)=2*(1)+2+(3)

BHD       (1,I) = Section No. bounding top of bulkhead I
          (2,I) = Section No. bounding bottom of bulkhead I
          (3,I) = Distance of bulkhead off center line
                  Longitudinal bulkheads are intercostal to
                  decks.BHD(1,I) and BHD(2,I) are integers

SPCNOM(I)
          Zero for transverse framing
          Nominal longitudinal spacing + modification for
               (I'th) section

ZINT      (1,I) = Height to lowest interface of section I
          (2,I) = Height to highest interface of section I
                  (including camber on main deck)
          (3,I) = Material type No.

ZIF       (1,I) = Height of I'th interface
          (2,I) = Material type No. below interface I
          (3,I) = Material type No. above interface I

NTYP(I)   Type No. for deck beam support condition

YSUP(I)   Location of side girder (Coordinate off center line)

HDSTR(I,J)
          Head load acting at stiffener location
```

HDSEAM(I,J)
Head load acting at plate seam location

PROPTY
(1,J) = Limiting primary stress (psi)
(2,J) = Limiting secondary stress (psi)
(3,J) = Limiting tertiary stress (psi)
(4,J) = Yield stress (psi)
(5,J) = Ultimate stress (psi)
(6,J) = Elastic modulus (psi)
(7,J) = Poisson ratio
(8,J) = Specific weight (lb./in^3)
(9,J) = Price (per pound) of plates
(10,J) = Price (per pound) of stiffeners
(11,J) = Labor factor (relative to mild steel)
J = Material type No.

AMITOT
(1) = Area
(2) = Moment
(3) = Inertia
(4) = Neutral axis height feet above keel
(5) = Section modulus to keel
(6) = Section modulus to deck

CONST
(1) = Deadrise angle (radians)
(2) = Height to bilge top
(3) = Length from center line to bottom of bilge turn
(4) = Length of bilge turn
(5) = Angular distance (radians) from CVK to bilge top along shell

GIRTH(I) Girths (lengths) of sections

AMI
(1,J,K) = Area
(2,J,K) = Moment
(3,J,K) = Inertia

STR
(1,J,K) = Stiffener Y coordinate
(2,J,K) = Stiffener Z coordinate
(3,J,K) = Proportionality constant
(4,J,K) = Material type No., filled by ASGSTR

SEAM
(1,J,K) = Girth (length) of seam
(2,J,K) = Y coordinate of seam
(3,J,K) = Z coordinate of seam

SPACE(I) Standard width; breaks up a width into standard spacings

KSTR(I) Number of stiffeners per section, for each section

HFHAT(I)	½ of full hatch width of deck (I)
DKHT(I)	Height of deck (I) above base line
HDABS(I)	Head (A.B.S.) for transverse structure for deck (I)
VLOAD(I)	Side column load (A.B.S.) or shear for deck (I)
TBEAM	(1,*,*) = Span (2,*,*) = Girder value or section modulus (3,*,*) = Area (*,1,*) = Side frame (*,2,*) = Deck frame or outboard deck frame (*,3,*) = Inboard deck frame, if present
HBEAM	(1,*,*) = Half span (2,*,*) = Girder value (3,*,*) = Area (*,1,*) = Hatch beam or outboard hatch beam (*,2,*) = Inboard hatch beam, if present
BOTF	(1) = Span (2) = Girder value (3) = Area
CLFLR	(1) = Span (2) = Thickness of CVK (3) = Area
REVFR	(1) = Span (2) = Girder value (3) = Area
WEB	(1) = Web depth (2) = Web thickness (3) = Flange width (4) = Flange thickness
WT(I)	Weight of transverse structure per linear foot for section (I)
IN1	(1) = 1 (2) = 1 (3) = 1 (4) = 2 (5) = 2 (6) = 2 (7) = 4 (8) = 5 This array controls entry point after data groups are changed.

ERR(I)	Error check array to check all input data groups present on first run
CON	(1) = /4HBASI/ (2) = /4HDETA/ (3) = /4HFRAM/ (4) = /4HPROP/ (5) = /4HMATE/ (6) = /4HSTRU/ (7) = /4HTRAN/ (8) = /4HCOST/ (9) = /4HRUN / (10) = /4HSTOP/
CLAB(I)	Cost of labor for section (I)
CMAT	(1) = Cost of plates (2) = Cost of stiffeners (3) = Cost of transverse structure (4) = Total cost of material
CWTT(I)	Converted weight of transverse structure for section (I)
AP(I)	Volume of plates in section (I)
AS(I)	Volume of stiffeners in section (I)
APC(I)	Modified volume, for fabrication ratioing, in section (I)
ASC(I)	Modified volume, for fabrication ratioing, in section (I)
WP(I)	Weight of plates in section (I)
WS(I)	Weight of stiffeners in section (I)
SF(I)	Areas of plates in section (I)
SCANT	Standard stiffener properties (1) = Web depth (2) = Web thickness (3) = Flange width (4) = Flange thickness (5) = Neutral axis (to keel) (6) = Area (7) = Inertia (8) = Flange modulus

SIG	(1) = σ_1 - Primary stress	
	(2) = σ_2 - Secondary stress	
	(3) = σ_3 - Tertiary stress	
NPLT(I)	Number of plates per section	
PLT	(1,*,*) = PLT thickness	
	(2,*,*) = Material type No.	
WTLMAT	(1,J) = Material type No. [Decimal]	
	(2,J) = Total weight for material J	
	J = Material type No.	
STSPAR	(1,J) = Bending moment (foot tons)	
	(2,J) = Limiting stress (psi)	
	(3,J) = Required section modulus - top	
	(4,J) = Required section modulus - bottom	
	J = Material type No.	

The program will fill this array if data is not provided. However, the limiting stress will be always the same for the same ship dimensions and will not depend on yield strength or other properties. These values are not used within the program but are displayed for comparison with program generated results.

APPENDIX 3

This appendix contains detailed information concerning make-up of data for the modified midship section program, version six.

PREPARATION OF DATA INPUT

The following pages present detailed instructions for preparation of data for computer input.

Each computer run must contain, as a minimum, one data set for each of the following groupings:

$MS BASIC GEOMETRY
$MS DETAIL GEOMETRY
$MS FRAMING SYSTEMS
$MS PROPERTIES OF MATERIALS
$MS STRUCTURAL DATA
$MS TRANSVERSE STRUCTURE PARAMETERS
$MS MATERIAL ASSIGNMENT
$MS COST DATA

The order of the sections is not important. Each is independent of the other; except that $MS COST DATA should always follow $MS PROPERTIES OF MATERIALS and each material in section $MS PROPERTIES OF MATERIALS must have a respective cost in the section $MS COST DATA. Even if all costs are the same, they must be repeated to equal the number of materials submitted. (Maximum number of materials is 5)

The program will test to see if all eight (8) groupings are filled before starting execution. If all are not filled a fatal error message will be generated, and execution will terminate.

Once the first execution is completed, any section may be changed and the execution repeated with the changed data. No recheck or recount of the eight groupings is made. The program continues to execute, on the command $MS RUN, utilizing whatever data is in the eight groupings; whether the data is the original or has been changed.

There are four levels of re-entry into the execution cycle, once the first execution has been completed. Table 16 which follows, contains a sample data deck setup and the values of the control arrays that the data generates. If any of the following data groupings are changed the program must recompute the ship's geometry: BASIC GEOMETRY, DETAIL GEOMETRY, and FRAMING SYSTEMS. This is the "most expensive" way to re-enter the execution cycle.

The function of the CON array is to determine what data group is being read. When any of the above three data groups are read the IN1 array is equal to one and entry point indicator (N1) is set equal to one. (N1 = 1) The entry point indicator is always set equal to the lowest value of the IN1 array that is encountered. On the first run this is naturally set to one.

The next level of entry is used when any of the following data groups are changed: PROPERTIES OF MATERIALS, MATERIAL ASSIGNMENT, and STRUCTURAL DATA. In this case the geometry does not have to be recalculated. These are the more useful data groups to change for parametric studies and they are "cheaper" to change than the first three. When TRANSVERSE STRUCTURE PARAMETERS or COST DATA are changed, even less re-calculation is necessary. These are the "cheapest" changes to make.

This "relative cost of change" of the various groupings should be borne in mind when setting up the sequencing of

TABLE 16

SAMPLE DATA DECK SETUP
(with control array values indicated)

			Branch Control Keys	
	Control card	Con(*)	IN1(*)	N1
$MS	BASIC GEOMETRY * * * = data cards	CON(1)=/4HBASI/	IN1(1)=1	1
$MS	DETAIL GEOMETRY * * *	CON(2)=/4HDETA/	IN1(2)=1	1
$MS	FRAME DATA * * *	CON(3)=/4HFRAM/	IN1(3)=1	1
$MS	PROPERTIES OF MATERIALS * * *	CON(4)=/4HPROP/	IN1(4)=2	1
$MS	MATERIAL ASSIGNMENTS * * *	CON(5)=/4HMATE/	IN1(5)=2	1
$MS	STRUCTURAL DATA * * *	CON(6)=/4HSTRU/	IN1(6)=2	1
$MS	TRANSVERSE FRAMING * * *	CON(7)=/4HTRAN/	IN1(7)=4	1
$MS	COST DATA * * *	CON(8)=/4HCOST/	IN1(8)=5	1
$MS	RUN	CON(9)=/4HRUN /		

TABLE 16 (cont')

	Control card	Con(*)	IN1(*)	N1
$MS	MATERIAL ASSIGNMENT * * *	CON(5)=/4HMATE/	IN1(5)=2	2
$MS	RUN	CON(9)=/4HRUN /		
$MS	COST DATA * * *	CON(5)=/4HCOST/	IN1(8)=5	5
$MS	MATERIAL ASSIGNMENT * * *	CON(5)=/4HMATE/	IN1(5)=2	2
$MS	RUN	CON(9)=/4HRUN /		
$MS	COST DATA * * *	CON(8)=/4HCOST/	IN1(8)=5	5
$MS	RUN	CON(9)=/4HRUN /		
$MS	STOP	CON(10)=/4HSTOP/		

data runs. If frame spacings are to be varied, for instance, the number of changes should be minimized. This means that all runs with common frame spacings should be run consecutively; changing material assignments, material properties or cost data, etc.

The following pages detail the identification of sections and the input formats for the various data groupings.

IDENTIFICATION OF SECTIONS

Number all decks starting with main deck, number inner bottom next after last deck, number the bottom shell next (this section follows the bottom shell shape up to the center vertical keel height or inner bottom height), number the side shell from inner bottom to lowest deck next, number the remaining side shells between decks next, number any longitudinal bulkheads next (from lowest to highest)

Section 1:	Deck 1 (main deck)
Section 2:	Deck 2
Section 3:	Deck 3
Section 4:	Inner Bottom
Section 5:	Bottom Shell
Section 6:	Side Shell, inner bottom to next upper deck
Section 7:	Side Shell, next higher side shell
Section 8:	Side Shell, next higher side shell
Section 9:	Longitudinal bulkhead

Refer to Figure 15, which follows, for illustration.

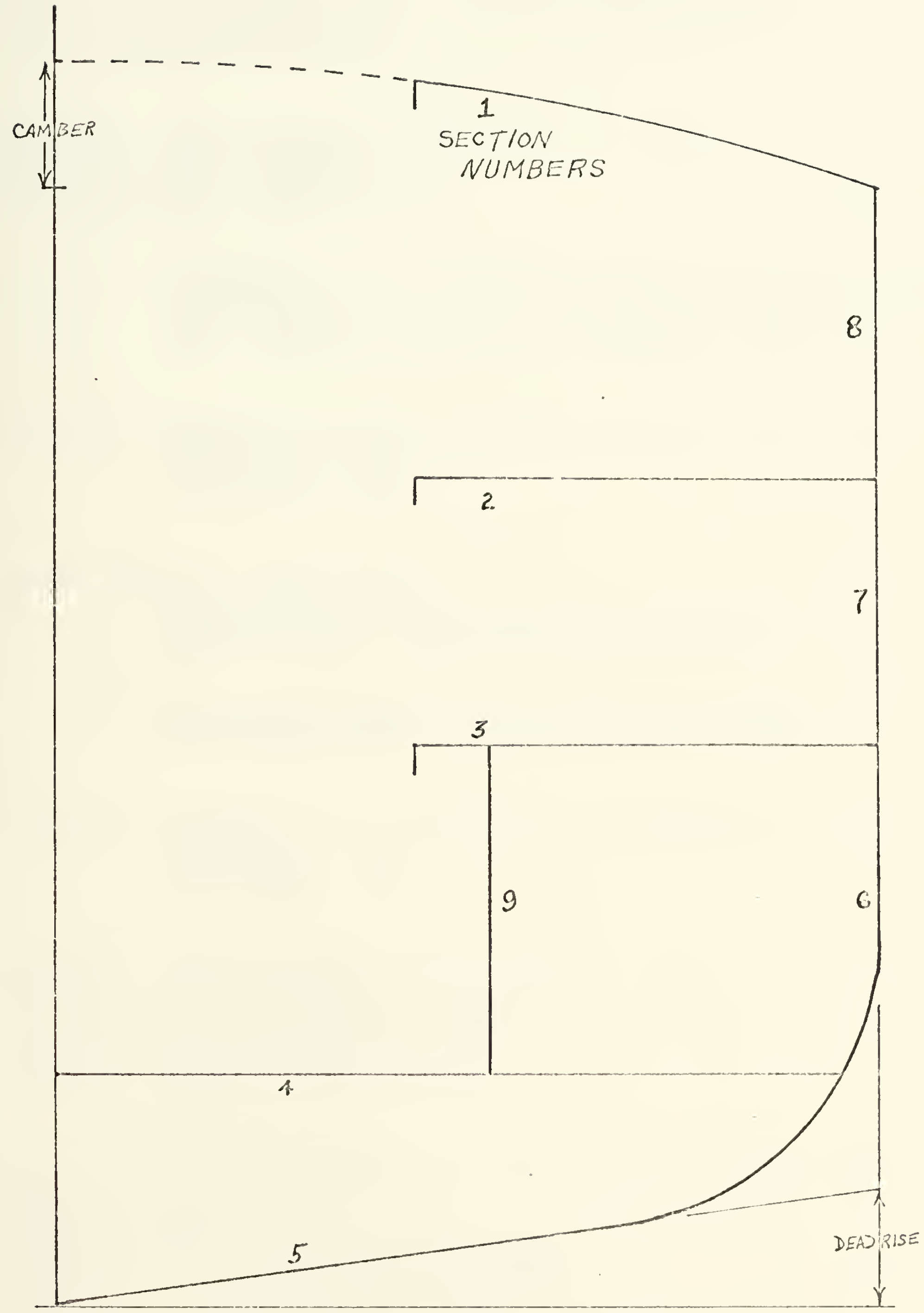

Fig. 15

Identification of Sections -
Typical Midship Cross-Section

$MS BASIC GEOMETRY

Guide to preparing basic geometry data input
(See subroutine BASIC)

Card 1
Columns 1-10; Length (ft)
Columns 11-20; Breadth (ft)
Columns 21-30; Depth (ft)
Columns 31-40; Draft (ft)

[Format will be shown here; the words integer or decimal will be used along with the standard Fortran notation: Decimal, 4F10.4]

Card 2
Column 5; Number of decks (less than 9, do not count inner bottom)
[Integer, I5]

Card 3
Inner bottom information:
a) If an inner bottom is to be included write; INNER BOTTOM, beginning in column 7

b) If no inner bottom is to be included, write; NO INNER BOTTOM, beginning in column 7

Card 4
Column 5; Number of longitudinal bulkheads in half section
[Integer, I5]

Card 5
Columns 1-10; Bilge radius (ft)
Columns 11-20; Center vertical keel (CVK) height (ft)
Columns 21-30; Deadrise (ft)
Columns 31-40; Camber (ft)
[Decimal, 4F10.2]

Card 6
Data for forming weight and cost ratios and print indicator KEY.
Columns 1-10; Base weight (tons/ft)
Columns 11-20; Base cost ($/ft)
Column 22; Print KEY=(one or zero)

KEY=0, Print all detail; KEY=1, Print summary only.
[Decimal 2F10.2, Integer I2]

Guide to preparing deck, hatch and longitudinal
bulkhead detail geometry (See subroutine DETAIL)

One card for each deck, in same order as numbered.
Columns 1-10; Deck height above baseline (ft)
Columns 11-20; Total hatch width, if any (ft)
[Decimal 2F10.2]

One card for each longitudinal bulkhead; longitudinal bulkheads are intercostal to decks
Column 5; Section number bounding top of bulkhead
Column 10; Section number bounding bottom of bulkhead
Columns 11-20; Distance of bulkhead off centerline (ft)
[Integer 2I5, Decimal F10.2]

$MS FRAMING SYSTEMS

Guide to preparing framing system data input
(See subroutine FRAME)

Card 1

```
     Columns  1-10; Transverse frame spacing (ft)
     Columns 11-20; Nominal longitudinal spacing (ft)
     Columns 21-30; Web spacing, if ship is longitudinally
                    framed (ft)
               [Decimal 3F10.2]
```

One card for each section

```
     Column      7; Framing system, type:
                 L; Longitudinally framed
                 T; Transversely framed
     Columns  8-20; Modification of nominal spacing (ie: + 0.3
                   or -0.6; ft added or subtracted from
                   nominal spacing) or leave blank for no
                   modification.
               [3X, Alpha A4, Decimal F13.2]
```

$MS PROPERTIES OF MATERIALS

Guide to preparing properties of materials data
(See subroutine PROMAT)

Card 1

Column 7; Number of materials to be read in.
[Integer I7]

One card 2 and one card 3 for each material

Card 2

Column 7; Material type number
Columns 8-17; Yield strength (psi)
Columns 18-27; Ultimate strength (psi)
Columns 28-37; Allowable stress factor
[Integer I7, Decimal 3F10.0]

Allowable stress factor, type:

0.0; program generates average of allowable stresses ratioed from medium steel values, based on yield and ultimate strengths.

Some other factor (positive); program will multiply medium steel values by factor.

Medium steel values are: σ_1=20000 (psi)

σ_2=27000 (psi)

σ_3=32000 (psi)

Card 3

Columns 1-12; Modulus of elasticity (psi)
Columns 13-22; Poisson ratio
Columns 23-32; Specific weight (lbs/in^3)
[Decimal F12.0, 2F10.0]

$MS STRUCTURAL DATA

Guide to preparing structural data input
(See subroutine STRUCT)

Card 1

Column 7; Number of different materials for which input data is provided.

Columns 8-17; Bending moment (ft-tons)

[Integer I7, Decimal F10.2]

One card for each material numbered above

Columns 1-10; Limit on highest primary stress allowable (psi)

Columns 11-20; Required section modulus at deck (in^2-ft^2)

Columns 21-30; Required section modulus at bottom (in^2-ft^2)

[Decimal 3F10.2]

Note:

1. This program will fill all the above data slots if none are submitted. You must enter 1 in column 7 of the first card and put a blank card in for card two. If the program computes the above data, it is based on medium steel formulas, and on ship dimensions. Therefore all material sections would give the same results, and only one will be printed.

2. This data is not used internally but is displayed for comparison with computer generated results.

3. For materials other than steel the minimum recommended data input is: a) Fill card 1, b) Fill limit stress (columns 1-10) on a card for each material, c) Program will fill remainder, which are simple division and unit changes.

4. If you desire to submit one required section modulus, for both top deck and bottom, place it in columns 11-20.

$MS TRANSVERSE STRUCTURE PARAMETERS

Guide to preparing transverse structure parameters input data (See subroutine TRANSV)

Card 1

Columns 1-10; Ratio of open to closed floors per hold (ie: 20 open and 5 closed-ratio=4.0)

Columns 11-20; Ratio of hatch length to hold length (ie: 60 ft. hold, 30 ft. hatch-ratio=0.5)

[Decimal 2F10.2]

One card for each deck

Columns 5; Type of support condition for deck thru-beams (See following illustrations)

Columns 6-24; Location of side support girder, if one exists (given as distance off centerline, in feet) (If none, leave blank)

[Interger I5, Decimal F19.2]

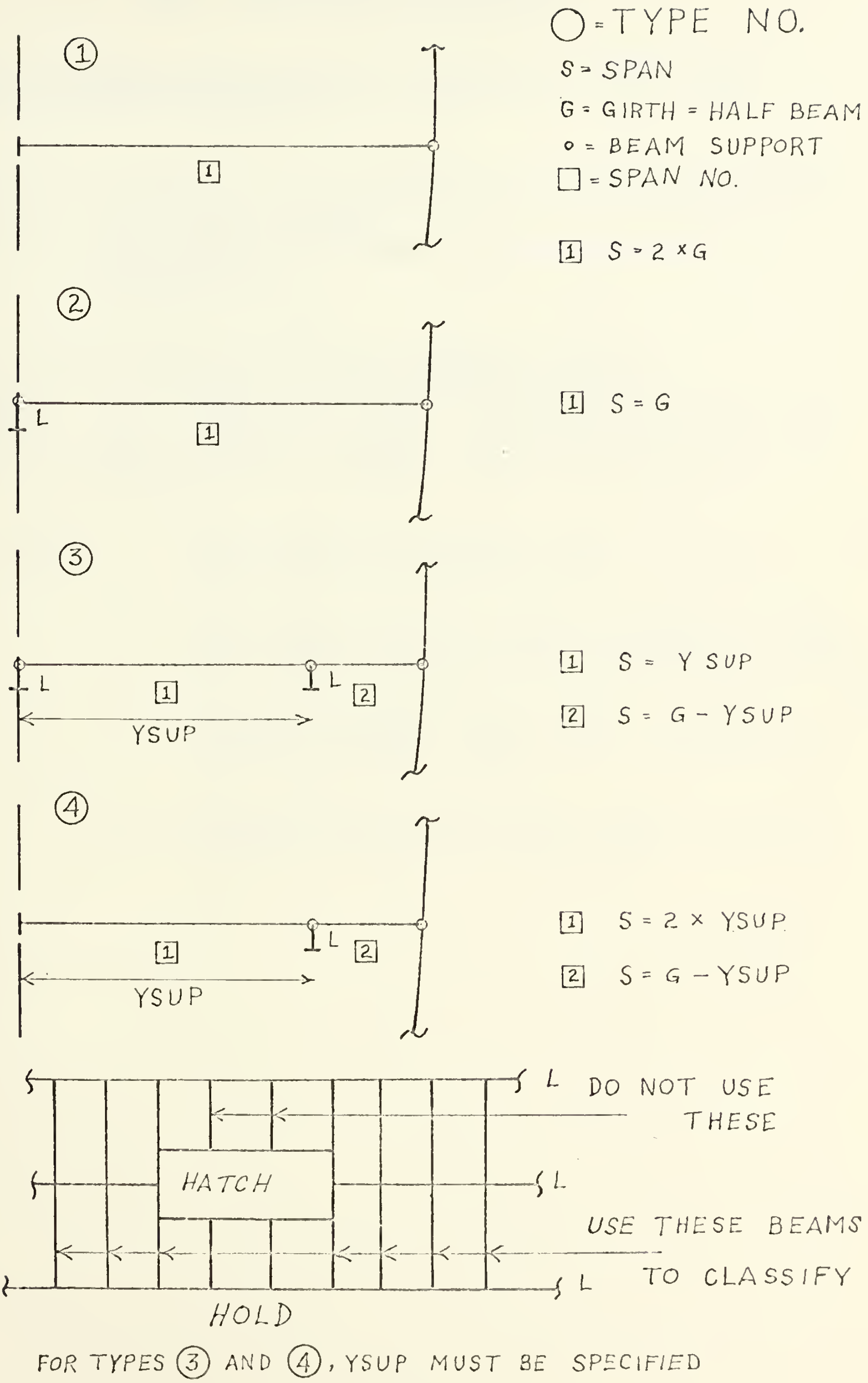

Fig. 16

Types of Support Conditions For Deck Thru-Beams

$MS MATERIAL ASSIGNMENT

Guide to preparing material assignment data input
(See subroutine MATASG)

Card 1

Column 7; Number of material areas that ship's depth is divided into.

Column 14; Material type number for all transverse structure.

[Integer 2I7]

One card for each material area numbered above.

Column 7; Material type number for area

Columns 8-20; Height to lower interface of area (ft)

Columns 21-30; Height to upper interface of area (ft)

[Integer I7, Decimal F13.2, F10.2]

Note:

1. The lowest interface must be 0.0 at the keel for the first area.
2. The uppermost interface height, at the main deck, must include camber, if any.
3. The upper interface of the previous area always becomes the lower interface of the next area above.
4. Cards must be ordered, lowest area to highest, keel to main deck.

$MS COST DATA

Guide to preparing cost input data
(See subroutine INCOST)

Card 1

Column 7; Number of materials for which cost data is provided
[Integer I7]

Note: This number must be the same as the number of materials for which data is provided in data group $MS PROPERTIES OF MATERIALS (ie: each material must have an individual set of cost data)

One card for each material numbered above

Column 7; Material type number
Columns 8-17; Cost of plates (Dollars per pound)
Columns 18-27; Cost of stiffeners (Dollars per pound)
Columns 28-37; Fabrication factor - Based on costs of fabrication of medium steel (ie: 1.2=20% greater fabrication cost)
[Integer I7, Decimal 3F10.3]

Last card

Columns 1-10; Labor wage rate (Dollars per man-hour)
[Decimal F10.2]

APPENDIX 4

This appendix contains a copy of a sample input data deck.

```
$MS   BASIC GEOMERTY                                                   DATA0001
528.5        76.        44.5        29.75                              DATA0002
    3                                                                  DATA0003
      INNER BOTTOM                                                     DATA0004
    0                                                                  DATA0005
9.5           4.42       0.         1.5                                DATA0006
6.236     2684.7      1                                                DATA0007
$MS   DETAILED ARRANGEMENTS                                            DATA0008
44.5         30.                                                       DATA0009
35.5         30.                                                       DATA0010
20.83        30.                                                       DATA0011
$MS   TRANSVERSE STRUCTURE PARAMETERS                                  DATA0012
0.0           0.667                                                    DATA0013
    2                                                                  DATA0014
    2                                                                  DATA0015
    2                                                                  DATA0016
$MS   PROPERTIES OF MATERIALS                                          DATA0017
      5                                                                DATA0018
      1   70000.   140000.    0.                                       DATA0019
20000000.      .3          .283                                        DATA0020
      2 150000.   300000.    0.                                        DATA0021
30000000.      .3          .283                                        DATA0022
      3 150000.   300000.    0.                                        DATA0023
40000000.      .3          .283                                        DATA0024
      4 150000.   160000.    0.                                        DATA0025
18000000.      .3          .283                                        DATA0026
      5 150000.   160000.    0.                                        DATA0027
18000000.      .3          .179                                        DATA0028
$MS   COST DATA                                                        DATA0029
      5                                                                DATA0030
      1   .075       .075       1.0                                    DATA0031
      2   .075       .075       1.0                                    DATA0032
      3   .075       .075       1.0                                    DATA0033
      4   .075       .075       1.0                                    DATA0034
      5   .075       .075       1.0                                    DATA0035
7.60                                                                   DATA0036
```

```
$MS    FRAMING DATA                                              DATA0037
1.5        0.0        0.0                                        DATA0038
       T                                                         DATA0039
       T                                                         DATA0040
       T                                                         DATA0041
       T                                                         DATA0042
       T                                                         DATA0043
       T                                                         DATA0044
       T                                                         DATA0045
       T                                                         DATA0046
$MS    STRUCTURAL DATA                                           DATA0047
       1  392000.                                                DATA0048
100000.   8780.                                                  DATA0049
$MS    MATERIAL ASSIGNMENT                                       DATA0050
       1     3                                                   DATA0051
       3   0.0        46.0                                       DATA0052
$MS    RUN                                                       DATA0053
$MS    FRAMING DATA                                              DATA0054
1.75       0.0        0.0                                        DATA0055
       T                                                         DATA0056
       T                                                         DATA0057
       T                                                         DATA0058
       T                                                         DATA0059
       T                                                         DATA0060
       T                                                         DATA0061
       T                                                         DATA0062
       T                                                         DATA0063
$MS    RUN                                                       DATA0064
$MS    FRAMING DATA                                              DATA0065
2.25       0.0        0.0                                        DATA0066
       T                                                         DATA0067
       T                                                         DATA0068
       T                                                         DATA0069
       T                                                         DATA0070
       T                                                         DATA0071
       T                                                         DATA0072
```

```
        T                                               DATA0073
        T                                               DATA0074
$MS     STRUCTURAL DATA                                 DATA0075
        1  392000.                                      DATA0076
46700.     18830.                                       DATA0077
$MS     MATERIAL ASSIGNMENT                             DATA0078
        1      1                                        DATA0079
        1   0.0         46.0                            DATA0080
$MS     RUN                                             DATA0081
$MS     FRAMING DATA                                    DATA0082
2.5         0.0         0.0                             DATA0083
        T                                               DATA0084
        T                                               DATA0085
        T                                               DATA0086
        T                                               DATA0087
        T                                               DATA0088
        T                                               DATA0089
        T                                               DATA0090
        T                                               DATA0091
$MS     STRUCTURAL DATA                                 DATA0092
        1  392000.                                      DATA0093
100000.   8780.                                         DATA0094
$MS     MATERIAL ASSIGNMENT                             DATA0095
        1      2                                        DATA0096
        2   0.0         46.0                            DATA0097
$MS     RUN                                             DATA0098
$MS     MATERIAL ASSIGNMENT                             DATA0099
        1      3                                        DATA0100
        3   0.0         46.0                            DATA0101
$MS     RUN                                             DATA0102
$MS     STRUCTURAL DATA                                 DATA0103
        1  392000.                                      DATA0104
53000.     16580.                                       DATA0105
$MS     MATERIAL ASSIGNMENT                             DATA0106
        1      4                                        DATA0107
        4   0.0         46.0                            DATA0108
```

```
$MS    RUN                                                              DATA0109
$MS    MATERIAL ASSIGNMENT                                              DATA0110
       1       5                                                        DATA0111
       5   0.0          46.0                                            DATA0112
$MS    RUN                                                              DATA0113
$MS    PROPERTIES OF MATERIALS                                          DATA0114
       3                                                                DATA0115
       1   32000.     60000.      0.                                    DATA0116
30000000.        .3          .283                                       DATA0117
       2   50000.     70000.      0.                                    DATA0118
30000000.        .3          .283                                       DATA0119
       3  100000.    115000.      0.                                    DATA0120
30000000.        .3          .283                                       DATA0121
$MS    COST DATA                                                        DATA0122
       3                                                                DATA0123
       1   .075         .075         1.0                                DATA0124
       2   .100         .100         1.05                               DATA0125
       3   .172         .172         1.2                                DATA0126
7.60                                                                    DATA0127
$MS    STRUCTURAL DATA                                                  DATA0128
       3  392000.                                                       DATA0129
20000.     43900.                                                       DATA0130
26000.     33800.                                                       DATA0131
36000.     24400.                                                       DATA0132
$MS    MATERIAL ASSIGNMENT                                              DATA0133
       3       1                                                        DATA0134
       3   0.0          9.5                                             DATA0135
       2   9.5          36.0                                            DATA0136
       3   36.0         46.0                                            DATA0137
$MS    RUN                                                              DATA0138
$MS    STOP                                                             DATA0139
```

APPENDIX 5

This appendix contains sample output of the computer program. The results are output generated by the input data shown in Appendix 4. The results of the first and last "ship" are included.

```
************************************************************************

            D A T A    F O R    S H I P    1
            --------------------------------

            NOTE --- DATA SECTIONS THAT ARE NOT SUBSEQUENTLY
                     REPEATED REMAIN CONSTANT FOR SHIPS THAT
                     FOLLOW SHIP NO. 1

************************************************************************
```

```
                 B A S I C   S H I P   G E O M E T R Y
                 -------------------------------------

                         (DIMENSIONS  ARE  FEET)

LENGTH ,  528.50   BREADTH ,   76.00   DEPTH ,   44.50   DRAFT ,   29.75

NUMBER OF DECKS   . .  3

THIS  SHIP  HAS  AN  INNER  BOTTOM

THERE ARE  0 LONG'L. BHDS. FOR 1/2 SECTION

BILGE RADIUS ,   9.50   C.V.K. HEIGHT,   4.42   DEADRISE,   0.0   CAMBER,   1.50

BASIC SHIP VALUES FOR RATIOS

BASIC WEIGHT (TONS PER FOOT) ,  6.236

BASIC COST (DOLLARS PER FOOT) ,  2684.7


PRINTED OUTPUT INDICATOR     KEY = 1

IF KEY = 0, PRINT ALL DETAIL
IF KEY = 1, PRINT SUMMARY ONLY.
```

D E T A I L E D   G E O M E T R Y

	DECK HT. AT SIDE (FT.)	HATCH HALF-WIDTH (FT.)
DECK 1	44.50	15.00
DECK 2	35.50	15.00
DECK 3	29.83	15.00

T R A N S V E R S E   S T R U C T U R E

OPEN TO CLOSED FLOOR RATIO	HATCH / HOLD LENGTH RATIO
0.0	0.67

TYPE SUPPORT (THRU BEAM)	SIDE GIRDER LOCATION OFF C.L. (FT.)
2	NO SIDE GIRDER
2	NO SIDE GIRDER
2	NO SIDE GIRDER

MATERIAL PROPERTIES

MATERIAL NO.	1	2	3	4	5
YIELD STRENGTH					
(POUNDS/SQUARE INCH)	70000.	150000.	150000.	150000.	150000.
ULTIMATE STRENGTH					
(POUNDS/SQUARE INCH)	140000.	300000.	300000.	160000.	160000.
LIMITING PRIMARY STRESS SIGMA 1					
(POUNDS/SQUARE INCH)	45208.	96874.	96874.	73541.	73541.
LIMITING SECONDARY STRESS SIGMA 2					
(POUNDS/SQUARE INCH)	61031.	130781.	130781.	99281.	99281.

LIMITING TERTIARY STRESS SIGMA 3					
(POUNDS/SQUARE INCH)	72333.	154999.	154999.	117666.	117666.
MODULUS OF ELASTICITY					
(POUNDS/SQUARE INCH)	20000000.	30000000.	40000000.	18000000.	18000000.
POISSON'S RATIO	0.300	0.300	0.300	0.300	0.300
UNIT WEIGHT (POUNDS/CUBIC INCH)	0.283	0.283	0.283	0.283	0.164

COST DATA

MATERIAL NO.	1	2	3	4	5
PRICE OF PLATES (DOLLARS/POUND)	0.075	0.075	0.075	0.075	0.075
PRICE OF STIFFS. (DOLLARS/POUND)	0.075	0.075	0.075	0.075	0.075
LABOR FACTOR (RELATIVE TO MILD STEEL)	1.00	1.00	1.00	1.00	1.00

SALARY (DOLLARS PER MAN HR.)= 7.60

F R A M I N G   D A T A

TRANSV. SP.= 1.50 FT., LONG'L SP.= 0.0 FT., NOMINAL WEB SP.= 0.0 FT.

SECTION 1 TRANSV. FRAMING

SECTION 2 TRANSV. FRAMING

SECTION 3 TRANSV. FRAMING

SECTION 4 TRANSV. FRAMING

SECTION 5 TRANSV. FRAMING

SECTION 6 TRANSV. FRAMING

SECTION 7 TRANSV. FRAMING

SECTION 8 TRANSV. FRAMING

STRUCTURAL DATA

STRUCTURAL DATA USED

BENDING MOMENT (FOOT-TONS)	LIMIT STRESS (LBS/SQ.IN)	REQUIRED SECTION MODULUS TOP (SQ.IN-FT)	BOTTOM (SQ.IN-FT)
392000.00	100000.00	8780.00	8780.00

M A T E R I A L   A S S I G N M E N T

NO. MAT'L SECTIONS= 1

MATERIAL TYPE	TOP (FT.)	BOTTOM (FT.)
3	46.C	C.0

MATERIAL FCR TRANSVERSE STRUCTURE IS NO.   3

****

SHIP 1 SUMMARY

MATERIAL SECTION ASSIGNMENTS
TOP , 3.0 SIDE , 3.0 BOTTOM , 3.0

LONGITUDINAL WEIGHTS

MATERIAL TYPE NO.	WEIGHT (TONS PER FOOT)
3.0	2.209

TRANSVERSE WEIGHT

MATERIAL TYPE NO.	WEIGHT (TONS PER FOOT)
3.0	1.540

TOTAL WEIGHT 3.749

COSTS (DOLLARS PER FOOT)

COST OF MATERIALS = 629.9

COST OF LABOR = 2116.6

TOTAL COST = 2746.5

WEIGHT RATIO = 0.601 COST RATIO = 1.023

RATIOS BASED ON --- BASE WEIGHT = 6.236
BASE COST = 2684.7

****

S E C T I O N   I N E R T I A   D E T A I L S

NEUTRAL AXIS HEIGHT = 19.50 FEET ABOVE KEEL

SECTION MODULUS ....

TO KEEL	=	21010.79	SQ.IN.-FT.
TO DECK	=	15455.44	SQ.IN.-FT.

PLATE THICKNESSES,

NO.	THICKNESS	METAL TYPE
DECK PLTS.		
(PLT. SECTION 1)		
1	0.41	3
2	0.41	3
3	0.42	3
4	0.42	3
DECK PLTS.		
(PLT. SECTION 2)		
1	0.32	3
2	0.32	3
3	0.32	3
4	0.32	3
DECK PLTS.		
(PLT. SECTION 3)		
1	0.30	3
2	0.30	3
3	0.30	3
4	0.30	3

NC.	THICKNESS	METAL TYPE

INNER BOTTOM PLTS.

(PLT. SECTION 4)

1	0.32	3
2	0.31	3
3	0.31	3
4	0.31	3
5	0.31	3
6	0.31	3
7	0.31	3
8	0.32	3

SHELL PLTS.

(PLT. SECTION 5)

1	0.38	3
2	0.35	3
3	0.35	3
4	0.35	3
5	0.35	3
6	0.34	3
7	0.31	3
8	0.30	3
9	0.31	3
10	0.31	3
11	0.31	3
12	0.31	3
13	0.31	3
14	0.34	3

D A T A   F O R   S H I P   8

NOTE --- DATA SECTIONS THAT ARE NOT SUBSEQUENTLY REPEATED REMAIN CONSTANT FOR SHIPS THAT FOLLOW SHIP NO. 1

MATERIAL PROPERTIES

MATERIAL NO.	1	2	3
YIELD STRENGTH (POUNDS/SQUARE INCH)	32000.	50000.	100000.
ULTIMATE STRENGTH (POUNDS/SQUARE INCH)	60000.	70000.	115000.
LIMITING PRIMARY STRESS SIGMA 1 (POUNDS/SQUARE INCH)	20000.	27292.	50416.
LIMITING SECONDARY STRESS SIGMA 2 (POUNDS/SQUARE INCH)	27000.	36844.	68062.

LIMITING TERTIARY STRESS SIGMA 3			
(POUNDS/SQUARE INCH)	32000.	43667.	80666.
MODULUS OF ELASTICITY			
(POUNDS/SQUARE INCH)	30000000.	30000000.	30000000.
POISSON'S RATIO	0.300	0.300	0.300
UNIT WEIGHT (POUNDS/CUBIC INCH)	0.283	0.283	0.283

COST DATA

MATERIAL NO.	1	2	3
PRICE OF PLATES (DOLLARS/POUND)	0.075	0.100	0.172
PRICE OF STIFFS. (DOLLARS/POUND)	0.075	0.100	0.172
LABOR FACTOR (RELATIVE TO MILD STEEL)	1.00	1.05	1.20

SALARY (DOLLARS PER MAN HR.)= 7.60

S T R U C T U R A L   D A T A

STRUCTURAL DATA USED

BENDING MOMENT (FOOT-TONS)	LIMIT STRESS (LBS/SQ.IN)	REQUIRED SECTION MODULUS TOP (SQ.IN-FT)	BOTTOM (SQ.IN-FT)
392000.00	20000.00	43900.00	43900.00
392000.00	26000.00	33800.00	33800.00
392000.00	36000.00	24400.00	24400.00

MATERIAL ASSIGNMENT

NO. MAT'L SECTIONS= 3

MATERIAL TYPE	TOP (FT.)	BOTTOM (FT.)
3	9.5	0.0
2	36.0	9.5
3	46.0	36.0

MATERIAL FOR TRANSVERSE STRUCTURE IS NO. 1

SHIP 8 SUMMARY

MATERIAL SECTION ASSIGNMENTS
TOP , 3.0 SIDE , 2.0 BOTTOM , 3.0

LONGITUDINAL WEIGHTS

MATERIAL TYPE NO.	WEIGHT (TONS PER FOOT)
2.0	1.447
3.0	2.549

TRANSVERSE WEIGHT

MATERIAL TYPE NO.	WEIGHT (TONS PER FOOT)
1.0	1.266

TOTAL WEIGHT 5.262

COSTS (DOLLARS PER FOOT)

COST OF MATERIALS = 1518.7

COST OF LABOR = 1867.5

TOTAL COST = 3386.3

WEIGHT RATIO = 0.844 COST RATIO = 1.261

RATIOS BASED ON --- BASE WEIGHT = 6.236
BASE COST = 2684.7

PLATE THICKNESSES ,

NO.	THICKNESS	METAL TYPE

DECK PLTS.

(PLT. SECTION 1)

1	0.61	3
2	0.62	3
3	0.62	3
4	0.63	3

DECK PLTS.

(PLT. SECTION 2)

1	0.55	2
2	0.55	2
3	0.55	2
4	0.55	2

DECK PLTS.

(PLT. SECTION 3)

1	0.49	2
2	0.47	2
3	0.47	2
4	0.47	2

NO.	THICKNESS	METAL TYPE
INNER BOTTOM PLTS.		
(PLT. SECTION 4)		
1	0.57	3
2	0.56	3
3	0.56	3
4	0.56	3
5	0.56	3
6	0.56	3
7	0.56	3
8	0.57	3
SHELL PLTS.		
(PLT. SECTION 5)		
1	0.66	3
2	0.58	3
3	0.58	3
4	0.58	3
5	0.58	3
6	0.58	3
7	0.57	3
8	0.56	3
9	0.66	2
10	0.66	2
11	0.71	2
12	0.71	2
13	0.85	3
14	0.91	3

S E C T I O N   I N E R T I A   D E T A I L S

```
NEUTRAL AXIS HEIGHT  =     19.67 FEET ABOVE KEEL

SECTION MODULUS ....
                          TO KEEL  =   36495.64 SQ.IN.-FT.
                          TO DECK  =   27275.13 SQ.IN.-FT.
```

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